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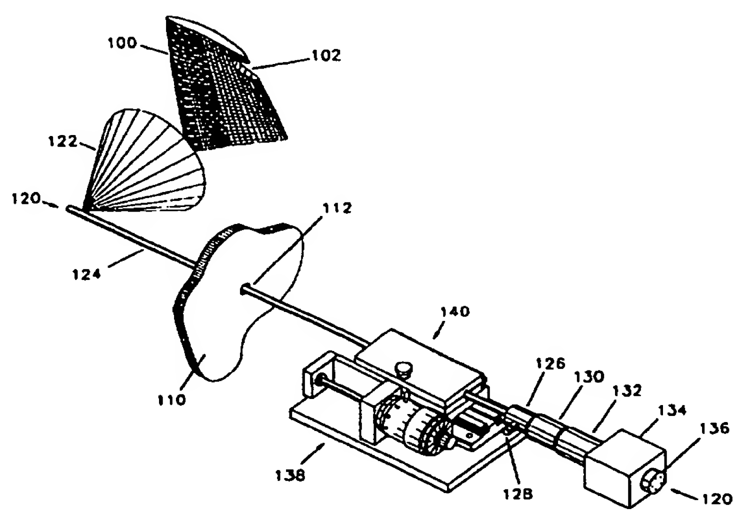

(57) Abstract

Spatial locations of individual points on an inaccessible object are determined by measuring two images acquired with one or more cameras which can be moved to a plurality of positions and orientations which are accurately determined relative to the instrument. Once points are located, distances are easily calculated. This new system offers accurate measurements with any convenient geometry, and with existing endoscopic apparatus. It also provides for the measurement of distances which cannot be contained within any single camera view. *Systematic errors* are minimized by use of a complete and robust set of calibration procedures. A standard measurement procedure automatically adjusts the measurement geometry to reduce random errors. A least squares calculation uses all of the image location and calibration data to derive the true three-dimensional positions of the selected object points. This calculation is taught explicitly for any camera geometry and motion.

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APPARATUS AND METHOD FOR MAKING ACCURATE THREE-DIMENSIONAL SIZE MEASUREMENTS OF INACCESSIBLE OBJECTS

Technical Field

This invention relates to optical metrology, specifically to the problem of making non-contact dimensional measurements of inaccessible objects which are viewed through an endoscope.

Background Art

A. Introduction

In the past several decades, the use of optical endoscopes has become common for the visual inspection of inaccessible objects, such as the internal organs of the human body or the internal parts of machinery. These visual inspections are performed in order to assess the need for surgery or equipment tear down and repair; thus the results of the inspections are accorded a great deal of importance. Accordingly, there has been much effort to improve the art in the field of endoscopes.

Endoscopes are long and narrow optical systems, typically circular in cross-section, which can be inserted through a small opening in an enclosure to give a view of the interior. They almost always include a source of illumination which is conducted along the interior of the scope from the outside (proximal) end to the inside (distal) end, so that the interior of the chamber can be viewed even if it contains no illumination. Endoscopes come in two basic types; these are the flexible endoscopes (fiberscopes and videoscopes) and the rigid borescopes. Flexible scopes are more versatile, but borescopes can provide higher image quality, are less expensive, are easier to manipulate, and are thus generally preferred in those applications for which they are suited.

While endoscopes (both flexible and rigid) can give the user a relatively clear view of an inaccessible region, there is no inherent ability for the user to make a quantitative measurement of the size of the objects he or she is viewing. There are many applications for which the size of an object, such as a tumor in a human body, or a crack in a machine part, is a critically important piece of information. Thus, there have been a number of inventions directed toward obtaining quantitative size information along with the view of the object through the endoscope.

The problem is that the accuracy to which the size of defects can be determined is poor with the currently used techniques. Part of the reason is that the magnification at which the defect is being viewed through the borescope is unknown. The other part of the problem is that the defects occur on surfaces which are curved in three dimensions, and the view through the endoscope is strictly two-dimensional.

Many concepts have been proposed and patented for addressing the need to make quantitative measurements through endoscopes. Only some of these concepts address the need to make the measurement in three dimensions. Few of these concepts have been shown to provide a useful level of measurement accuracy at a practical cost.

Probably the simplest approach to obtaining quantitative object size information is to attach a physical scale to the distal end of the endoscope, and to place this scale in contact with the object to be measured. The problems with this are that it is often not possible to insert the scale through the available access hole, that the objects of

interest are almost never flat and oriented in the correct plane so that the scale can lie against them, that it is often not possible to manipulate the end of the endoscope into the correct position to make the desired measurement, and that it is often not permissible to touch the objects of interest.

These problems have driven work toward the invention of non-contact measurement techniques. There have been a number of systems patented which are based on the principle of optical perspective, or more fundamentally, on the principle of triangulation.

B. Non-Contact Measurements Using Triangulation and Perspective

What I mean by "use of perspective" is the use of two or more views of an object, obtained from different viewing positions, for dimensional measurement of the object. By "dimensional measurement", I mean the determination of the true three-dimensional (height, width, and depth) distance between two or more selected points on the object.

To perform a perspective dimensional measurement, the apparent positions of each of the selected points on the object are determined in each of the views. This is the same principle used in stereoscopic viewing, but here I am concerned with making quantitative measurements of object dimensions, rather than obtaining a view of the object containing qualitative depth cues. As I will teach, given sufficient knowledge about the relative locations, orientations and imaging properties of the viewing optical systems, one can accurately determine the locations of the selected points in a measurement coordinate system. Once these locations are known, one then simply calculates the desired distances between points by use of the well-known Pythagorean Theorem.

Perspective is related to and based on triangulation, but triangulation is also the principle behind making any measurement of distance using the measurement of angles.

The earliest related art of which I am aware is described in US Patent 4,207,594, (1980) to Morris and Grant. The basic approach of this work is to measure the linear field of view of a borescope at the object, then scale the size of the object as measured with video cursors to the size of the field of view as measured with the same cursors. The linear field of view is measured by determining the difference in borescope insertion depth between alignment of the two opposite edges of the field of view with some selected point on the object.

A major problem with this approach is that it cannot determine the depth of the object. In fact, the patent specifies that the user has to know the angle that the plane of the object makes with respect to the plane perpendicular to the borescope line of sight. This information is almost never available in any practical measurement situation. A second problem is that this technique gives valid results only if the optical axis of the borescope is oriented precisely perpendicular to the length of the borescope.

In US Patent 4,702,229, (1987) Zobel describes a rigid borescope free to slide back and forth between two fixed positions inside an outer mounting tube, to measure the dimensions of an object. As with Morris and Grant, Zobel does not teach the use of the principle of perspective, and thus discusses only the measurement of a flat object, oriented perpendicular to borescope line of sight.

US Patent 4,820,043, (1989) to Diener describes a measurement scope after Zobel (4,702,229) with the addition of an electronic transducer on the measurement scale, an instrumented steering prism at the distal end, and a calculator. The principle is that once the distance to the object is determined by the translation of the

borescope proper according to Zobel, then the object size can be determined by making angular size measurements with the steerable prism. Again, there is no consideration of measurement of the depth of the object.

US Patent 4,935,810, (1990) to Nonami and Sonobe shows explicitly a method to measure the true three-dimensional distance between two points on an object by using two views of the object from different perspectives. They use two cameras separated by a fixed distance mounted in the tip of an endoscope, where both cameras are aligned with their optical axes parallel to the length of the endoscope. The fixed distance between the cameras causes the measurement error to be rather large for most applications, and also places a limit to how close an object to be measured can be to the endoscope. In addition, the two cameras must be precisely matched in optical characteristics in order for their technique to give an accurate measurement, and such matching is difficult to do.

All four of these prior art systems assume that the measurement system is accurately built to a particular geometry. This is a significant flaw, since none of these patents teach one how to achieve this perfect geometry. That is, if one attempts to use the technique taught by Nonami and Sonobe, for instance, one must either independently develop a large body of techniques to enable one to build the system accurately to the required geometry, or one must accept measurements of poor accuracy. None of these inventors teach how to calibrate their system, and what is more, one cannot correct for errors in the geometry of these systems by a calibration process because none of these systems include any provision for incorporating calibration data into the measurement results.

In US Patent 5,575,754, (1996), Konomura teaches a system of perspective dimensional measurement which is based on moving a rigid borescope along a straight line in a manner similar to Zobel, but now the borescope is moved by a variable distance to obtain the two views of the object. Konomura recognizes that using a variable distance between the viewing positions allows one to obtain lower measurement errors, in general. Konomura also recognizes the necessity of compensating for the effects of certain aspects of the actual measurement geometry being used, thus implicitly allowing for incorporation of some calibration data into the measurement result. The patent does not teach how to do the calibration, and unfortunately, the compensation technique that is taught is both incomplete and incorrect. In addition, the motion technique taught by Konomura is not inherently of high precision, that is, it is not suitable for making dimensional measurements of high accuracy. Konomura's apparatus for holding the borescope allows the scope to be rotated with respect to the apparatus in order to align the view with objects of interest, but there is no consideration given to the repeatability of borescope positioning which is necessary in order to assure accuracy in the measurement.

All of these measurement techniques are limited to objects which are small enough to be completely contained within the field of view of the endoscope. In addition, there are other applications of interest which simply cannot be addressed by any of these techniques, for instance where the object has a shape and an orientation such that the two ends of a dimension of interest cannot both be viewed from any single position.

Disclosure of the Invention

While the prior art in this area is extensive, there remains a need for a measurement system which can provide truly accurate dimensional measurements on an inaccessible object. By "truly accurate", I mean that the level of accuracy should be limited only by the technology of mechanical metrology and by unavoidable random errors made by the most careful user. There also remains a need for a usefully accurate measurement at low cost. By "usefully accurate", I mean that the accuracy of the measurement should be adequate for the purposes of most common industrial applications. By "low cost", I mean that with some embodiments, the user should be able to add this measurement capability to his or her existing remote visual inspection capability with a lower incremental expenditure than is required with the prior art. There also remains a need for a measurement system which can be applied to a wider range of situations than has been addressed in the prior art.

Meeting these goals inherently requires that the measurement should not depend on an apparatus being built precisely to a particular geometry, nor to particular optical characteristics. Instead, the measurement system must be sufficiently complete and comprehensive so that the apparatus is capable of being calibrated and there must exist a sufficient set of methods to perform this calibration.

In one aspect, therefore, my invention provides a method of locating an object point of interest in three dimensional space using one or more cameras which can be moved among any of a plurality of predetermined relative viewing positions and orientations. "Predetermined" in this case means that these quantities are determined before the measurement result is calculated, and that the measurement requires no auxiliary information from or about the object. Because the camera(s) can be moved, the viewing positions that are used to perform a particular point location can be chosen during the measurement, according to the requirements of the particular measurement being performed. The apparent locations of the images of the point as viewed from two different positions are measured and, using the predetermined geometry of the system, and the predetermined optical characteristics of the camera(s), a fully three-dimensional, least squares estimate of the location of the point is calculated. The geometry of the measurement is completely general, and there are identified a complete set of parameters which can be calibrated in order to ensure an accurate measurement. A complete set of calibration methods is taught. This aspect of my invention enables one to accurately locate a point using whatever measurement geometry is most advantageous for the application.

In another aspect, the invention provides a method in which the motion(s) of the camera(s) is (are) constrained to one of a variety of specific paths. According to this aspect, different camera paths have advantages for different measurement applications. Also, according to this aspect, it is possible to determine the orientation(s) of the camera(s) with respect to its (their) path(s) of motion in a calibration procedure, and to take into account this (these) orientation(s) in the determination of the location of the point of interest. In addition, according to this aspect, it is possible to determine errors in the actual motion(s) with respect to the ideal motion(s) and to also take these errors into account in locating the point. Thus, this aspect allows one, for instance, to accurately locate a point using existing endoscopic hardware which was not originally designed to make measurements, and which is not built according to the assumptions and requirements of the prior art.

In another aspect, the method of locating a point of interest is used to determine the three-dimensional distances between points of interest on a remote object, where all the points of interest can be contained within a

single view of the camera(s) being used. This aspect allows one to, for instance, perform an improved perspective dimensional measurement under conditions similar to those addressed by the prior art.

In another aspect, the method of locating a point of interest is used to determine the three-dimensional distance between a pair of points on an object, where the two points of the pair cannot necessarily be contained within any single view of the camera being used. This aspect allows one to perform a new mode of perspective dimensional measurement which has the capability of accurately measuring distances which are impossible to measure at all in the prior art. This aspect also offers the capability of performing the most precise dimensional measurements achievable with my system.

In another aspect, my invention provides a method of locating a point of interest in three-dimensional space using a single camera, subjected to a substantially pure translation between two viewing positions, in which the first and second viewing positions are selected so that the point of interest is viewed first near the edge of one side of the field of view and secondly near the edge of the opposite side of the field of view. This aspect allows one to automatically obtain one of the key conditions required for achievement of the lowest random error (highest precision) in the perspective dimensional measurement.

In still another aspect, the invention provides an apparatus for measuring the three-dimensional distances between points on an inaccessible object, wherein the apparatus includes a borescope supported by a linear motion means, a driving means which controls the position of the linear motion means, and a position measurement means which determines the position of the linear motion means. Here the improvement is that a linear motion means is used which provides a motion of very high accuracy. In an embodiment, one may select the driving means to be an actuator, for instance an air cylinder. Also the position measurement means may be embodied as a linear position transducer.

In another aspect, the invention provides an apparatus for measuring the three-dimensional distances between points on an inaccessible object, wherein the apparatus includes a borescope supported by a linear motion means, a driving means which controls the position of the linear motion means, a position measurement means which determines the position of the linear motion means, and wherein the improvement is the use of a lead screw and matching nut as the driving means. In an embodiment, one may embody both the driving means and the position measurement means as a micrometer.

In another aspect, the invention provides apparatus according to the previous two aspects, but wherein the borescope includes a video camera, and wherein the video camera is correctly rotationally oriented with respect to the borescope in order to satisfy a second key condition required for the achievement of measurements of the highest feasible precision.

In still another aspect, the invention provides an apparatus for measuring the three-dimensional distances between points on an inaccessible object, wherein the apparatus includes a video camera mounted on a linear translation means, and wherein this assembly is mounted on the distal end of a rigid probe to form an electronic measurement borescope. This aspect thus provides a self-contained measurement system, one which can provide measurements of much higher accuracy than those provided by prior art systems.

In another aspect, the invention provides an apparatus for measuring the three-dimensional distances between points on an inaccessible object, wherein the apparatus includes a video camera mounted on a linear translation means, and wherein this assembly is mounted at the distal end of a flexible housing to form an electronic

measurement endoscope. This aspect also provides a self-contained measurement system with high measurement accuracy, but in this case in a flexible package that can reach inaccessible objects under a wider range of conditions.

In another aspect, the invention provides an apparatus for measuring the three-dimensional distances between points on an inaccessible object which comprises a camera and a support means for moving the camera along a straight translation axis, wherein the camera can also be rotated about a rotation axis for convenient alignment with an object of interest, and wherein the improvement comprises a means for measuring an angle of rotation about the rotation axis and also a means for incorporating the measured angle into the result of the perspective measurement. The rotation in this case is made prior to (and not during) the measurement process. This aspect then allows a user to make accurate dimensional measurements while allowing rotation of the camera for convenient alignment while also requiring only infrequent calibrations.

In still another aspect, the invention provides an apparatus for measuring the three-dimensional distances between points on an inaccessible object which comprises a substantially side-looking borescope, where the borescope can be translated along a straight line and where the borescope can also be rotated about a rotational axis, wherein the improvement comprises the arrangement of the rotation axis to be accurately aligned with the translation axis. This aspect also enables a user to make accurate dimensional measurements while allowing rotation of the borescope while also requiring only infrequent alignment calibrations.

Further objects, advantages, and features of my system will become apparent from a consideration of the following description and the accompanying schematic drawings.

Brief Description of the Drawings

Figure 1 shows the definitions of various quantities related to a rigid borescope.

Figure 2 depicts the change in perspective when viewing a point in space from two different positions.

Figure 3 depicts the imaging of a point in space with a camera.

Figure 4 is a perspective view of the mechanical portion of a first embodiment of the invention and its use in a typical measurement situation.

Figure 5 is a detailed perspective view of the mechanical portion of the first embodiment of the invention.

Figure 6 is a cross-sectional view of a portion of the structure shown in Figure 5.

Figure 7 is a block diagram of the electronics of the first embodiment of the invention.

Figure 8 is a view of the video monitor as seen by the user during the first stage of a first distance measurement procedure.

Figure 9 is a view of the video monitor as seen by the user during the second stage of a first distance measurement procedure.

Figure 10 shows two views of the video monitor as seen by the user during the first stage of a second distance measurement procedure.

Figure 11 shows the two views of the video monitor as seen by the user during the second stage of a second measurement procedure.

Figure 12 shows a general relationship between the viewing coordinate systems at the two viewing positions.

Figure 13 depicts a second mode of the dimensional measurement process taught by the present invention.

Figure 14 is a block diagram of the electronics of a second embodiment of the invention.

Figure 15 is a front view of the mechanical portion of a second embodiment of the invention.

Figure 16 is a plan view of the mechanical portion of a second embodiment of the invention.

Figure 17 is a rear view of the mechanical portion of a second embodiment of the invention.

Figure 18 is a left side elevation view of the mechanical portion of a second embodiment of the invention.

Figure 19 is a right side elevation view of the mechanical portion of a second embodiment of the invention.

Figure 20 is a perspective view of the mechanical portion of a third embodiment of the invention.

Figure 21 is a plan view of the internal structures at the distal end of the third embodiment.

Figure 22 is a left side elevation view of the internal structures at the distal end of the third embodiment.

Figure 23 is a right side elevation view of the internal structures at the distal end of the third embodiment.

Figure 24 is a plan view of the internal structures at the proximal end of the third embodiment.

Figure 25 is a left side elevation view of the internal structures at the proximal end of the third embodiment.

Figure 26 is a right side elevation view of the internal structures at the proximal end of the third embodiment.

Figure 27 is a proximal end elevation view of the internal structures at the proximal end of the third embodiment.

Figure 28 is a block diagram of the electronics of the third embodiment.

Figure 29 is a plan view of the internal structures at the distal end of a fourth embodiment.

Figure 30 is a left side elevation view of the internal structures at the distal end of the fourth embodiment.

Figure 31 depicts the perspective measurement mode 2 process when a camera moves in a straight line path, but when the orientation of the camera is not fixed.

Figure 32 depicts the perspective measurement mode 1 process when a camera is constrained to a circular path which lies in the plane of the camera optical axis.

Figure 33 shows an endoscope which implements a circular camera path where the camera view is perpendicular to the plane of the path.

Figure 34 depicts the measurement mode 2 process with a general motion of the camera.

Figure 35 depicts the measurement of a distance with a combination of circular camera motion and measurement mode 2.

Figure 36 illustrates a group of calibration target points being viewed with a camera located at an unknown position and orientation.

Figure 37 illustrates the process of calibration of rotational errors of the translation stage used in the third and fourth embodiments.

Figure 38 shows an enlarged view of the components mounted to the translation stage during the calibration process depicted in Figure 37.

Figure 39 represents an example of the change in alignment between a perspective displacement vector, **d**, and a borescope's visual coordinate system that can occur if the borescope lens tube is not straight.

Figure 40 depicts the change in alignment between the perspective displacement and the visual coordinate system that can occur if the borescope is rotated about an axis that is not parallel to the perspective displacement.

Figure 41 is a perspective view of a first variant of borescope/BPA embodiments of the invention.

Figure 42 is a perspective view of an embodiment of a strain-relieving calibration sleeve.

Figure 43 is an end elevation view of a test rig for determining the alignment of a V groove with respect to the translation axis of a translation stage.

Figure 44 depicts the process of determining the alignment errors caused by imperfections in the geometry when a cylinder rotates in a V groove.

Figure 45 is a perspective view of the mechanical portion of a second variant of borescope/BPA embodiments of the invention.

Figure 46 depicts the relationships between the three Cartesian coordinate systems used in analyzing the effects of a misalignment of the borescope axis of rotation with respect to the perspective displacement.

Figure 47 shows the relationship of the borescope visual and mechanical coordinate systems.

Best Modes for Carrying out the Invention

A. Explanation of the Prior Art of Perspective Measurement and its Limitations

In order to clarify the discussion of the perspective measurement and the problems in the prior art, I will carefully define the terms and processes being used.

Figure 1 depicts the distal end of a rigid borescope 2 together with a representation of its conical optical field of view 4. Field of view 4 is defined by a nodal point 10 of the borescope optical system and a cone that has its apex there. The "nodal point" of an optical system is that point on the optical axis of the system for which an optical ray incident at the point is not deviated by the system.

The axis of conical field of view 4 is assumed to coincide with the optical axis 8. Figure 1 is drawn in the plane which both contains optical axis 8 and which is also parallel to the mechanical centerline of the borescope 6. The apex angle, 11, of the field of view cone is denoted as FOV, half that angle, 12, is denoted as HFOV, and the "viewing angle" of the borescope with respect to the centerline of the scope, 14, is denoted as VA . Viewing angle 14 is defined to be positive for rotation away from the borescope centerline, to match standard industry practice.

The change in perspective when viewing a point in space from two different positions is depicted in Figure 2. A right handed global Cartesian coordinate system is defined by the unit vectors $\hat{x}$, $\hat{y}$, and $\hat{z}$. A particular point of interest, P_i, at $\mathbf{r} = x\,\hat{x} + y\,\hat{y} + z\,\hat{z}$, is viewed first from position P1, then from position P2. The coordinate system has been defined so that these viewing positions are located on the x axis, equally spaced on either side of the coordinate origin. I call the distance d between the viewing positions the *perspective baseline*, and I call the vector $\mathbf{d} = d\,\hat{x}$ the *perspective displacement.*

According to the known perspective measurement technique, viewing coordinate systems are set up at P1 and P2, and both of these coordinate systems are aligned parallel to the global coordinates defined in Figure 2.

As part of the perspective measurement, the object point of interest is imaged onto the flat focal plane of a camera, as depicted in Figure 3. In Figure 3, a point 16 is imaged with a lens that has a nodal point 10. An image plane 18 is set up behind nodal point 10, with the distance from the plane to the nodal point being denoted as i. This distance is measured along a perpendicular to image plane 18, and is often referred to as the effective focal length of the camera. The nodal point is taken as the origin of a Cartesian coordinate system, where the z axis is defined as that perpendicular to the image plane that passes through the nodal point. The z axis is the optical axis of the camera.

In the model of Figure 3, the camera lens is considered as a paraxial thin lens. According to paraxial optics, rays that strike the nodal point of the lens pass through it undeviated. It is important to realize that any imaging optical system, including that of an endoscope, can be represented as a camera as shown in Figure 3.

For object point 16 at (x, y, z) one can write these coordinates in standard spherical polar coordinates about the nodal point as:

$$x = o' \sin\theta \cos\phi \quad y = o' \sin\theta \sin\phi \quad z = o' \cos\theta \tag{1}$$

where o' is the distance from the object point to the nodal point, and the polar angle θ is shown in Figure 3.

By the properties of the nodal point, the angles of the transmitted ray will remain the same and one can write the image point location 20 as:

$$x_{im} = -i' \sin\theta \cos\phi \quad y_{im} = -i' \sin\theta \sin\phi \quad z_{im} = -i \tag{2}$$

But $i = i' \cos\theta$ so that:

$$x_{im} = -\frac{i \sin\theta \cos\phi}{\cos\theta} = -\frac{i\,x}{o' \cos\theta} = -\frac{i\,x}{z} \tag{3}$$

$$y_{im} = -\frac{i \sin\theta \sin\phi}{\cos\theta} = -\frac{i\,y}{o' \cos\theta} = -\frac{i\,y}{z} \tag{4}$$

That is, the transverse coordinates of the image point (x_{im},y_{im}), are directly proportional to the transverse coordinates of the object point.

When considering the performance of a real optical system, as opposed to a paraxial model, the image of an object point will be blurred by what are called point aberrations and it will be displaced by what are called field aberrations. I define the location of the image point to be the location of the centroid of the blur spot, and I refer to the extent to which Equations (3) and (4) do <u>not</u> hold for the image point centroid as the *distortion* of the optical system. Clearly, consideration of the distortion of the optical system is important for making accurate measurements, and this was recognized in some of the prior art. I will later show how to determine the distortion and how to take it into account in the measurement.

Considering now the view from position P1 in Figure 2, one may write:

$$x_{im1} = -\frac{i\,x_{v1}}{z_{v1}} \; ; \; y_{im1} = -\frac{i\,y_{v1}}{z_{v1}} \tag{5}$$

where (x_{v1}, y_{v1}, z_{v1}) are the coordinates of the point of interest in the viewing coordinate system at P1. Similar expressions in terms of (x_{v2}, y_{v2}, z_{v2}) hold for the view at P2. Using the facts that $x_{v1} = x + \frac{d}{2}$, $x_{v2} = x - \frac{d}{2}$, $y_{v1} = y_{v2} = y$, and $z_{v1} = z_{v2} = z$, the solution of the four equations for the position of the point P, in global coordinates is:

$$z = \frac{-i\,d}{x_{im1} - x_{im2}} \tag{6}$$

$$x = \left(\frac{-z}{2\,i}\right)(x_{im1} + x_{im2})$$

$$y = \left(\frac{-z}{i}\right)(y_{im1}) = \left(\frac{-z}{i}\right)(y_{im2})$$

To make a measurement of the true, three dimensional distance between two points, A and B, in space, one has simply to measure the three dimensional position (x, y, z) of each point according to (6) and then to calculate the distance between them by the well known formula:

$$r = \sqrt{(x_A - x_B)^2 + (y_A - y_B)^2 + (z_A - z_B)^2} \tag{7}$$

This is the perspective measurement process taught by both Nonami and Sonobe in US Patent 4,935,810 and by Konomura in US Patent 5,575,754. Nonami and Sonobe use two cameras, one located at each of points P1 and P2 in Figure 2, while Konomura uses a single camera, translated along a straight line from P1 to P2.

Unfortunately, this known process has severe limitations. First, it will give accurate results only when the optical (z) axes of the cameras at both viewing positions are perfectly aligned along the global z axis. Secondly, it

also requires that the x axes of the cameras at both viewing positions be aligned perfectly along the perspective displacement.

In the case of Nonami and Sonobe, they do not teach how to achieve these necessary conditions. In addition, for their system the two cameras must be identical in both distortion and effective focal length in order to give an accurate measurement. They do not teach how to achieve those conditions either. As an additional difficulty with their system, Nonami and Sonobe deal with the redundancy inherent in the final equation of (6) by specifically teaching that only three of the four available apparent point location measurements should be used for each point location determination. In fact, they go to a great deal of trouble to ensure that only one of the image point y position measurements can be used. This amounts to throwing information away and in general, considering the effects of measurement errors, it is not a good idea.

In the case of Konomura, where there is only one camera, which is a borescope, the first necessary condition means that the viewing angle of the borescope must be accurately equal to 90° in order for the measurement to be accurate. Konomura realizes that this is a problem and teaches the use of the following equation for the case where the viewing angle is not 90°:

$$d' = d\cos(\mathrm{VA} - 90°) \tag{8}$$

Unfortunately, use of Equation (8) does not correctly take into account the change in the perspective measurement which occurs when the camera viewing angle is not equal to 90°. In addition, Konomura makes no provision for ensuring that the measurement x axis of the camera is aligned with the perspective displacement. Since the camera is a standard video borescope, in which the video sensor could be attached to the borescope proper at any rotational angle, there is little likelihood that the x axis of the video sensor will be aligned to the perspective displacement.

Konomura has nothing to say about how to handle the redundant equations in (6).

B. Description of a First Embodiment

Figure 4 shows a view of the mechanical portion of a basic embodiment of my system and its use in a typical measurement situation. In Figure 4, an object 100 with a damaged area or feature of interest 102 is being viewed with a video borescope system 120. Object 100 is completely enclosed by an enclosure 110. In Figure 4 only a small portion of the wall of enclosure 110 is shown. The borescope has been inserted through an inspection port 112 in the wall of enclosure 110.

The borescope is supported by and its position is controlled by a mechanical assembly that I call the *borescope positioning assembly* (BPA), which is denoted by 138 in Figure 4.

Several features of video borescope system 120 are shown in Figure 4 to enable a better understanding of my system. The configuration shown is meant to be generic, and should not be construed as defining a specific video borescope to be used.

Conical field of view 122 represents the angular extent of the field visible through the borescope. The small diameter, elongated lens tube 124 comprises the largest portion of the length of the borescope. The remainder of the borescope is comprised successively of an illumination interface adapter 126, a focusing ring 130, a video adapter 132, and a video camera back or video sensor 134. Video camera back 134 represents every element of a closed circuit television camera, except for the lens. Video adapter 132 acts to optically couple the image formed

by the borescope onto the image sensing element of video camera back 134 as well as serving as a mechanical coupling.

Illumination adapter 126 provides for the connection of an illumination fiber optic cable (not shown) to the borescope through a fiber optic connector 128. The illumination (not shown) exits lens tube 124 near the apex of field of view cone 122 to illuminate objects contained within cone 122.

A camera connector 136 connects video camera back 134 to its controller (not shown) through a cable which is also not shown.

The portion of BPA 138 which directly supports the borescope is a clamp assembly 140, which clamps lens tube 124 at any convenient position along its length, thereby supporting the weight of borescope 120 and determining its position and orientation. BPA 138 is itself supported by a structure which is attached to enclosure 110 or to some other structure which is fixed in position with respect to object 100. This support structure is not part of the present invention.

BPA 138 is shown in more detail in Figure 5. Lens tube 124 has been removed from clamp 140 in this view for clarity. Clamp 140 is comprised of a lower V - block 142, an upper V - block 144, a hinge 148, and a clamping screw 150. The upper V - block is lined with a layer of resilient material 146, in order that the clamping pressure on the lens tube 124 can be evenly distributed over a substantial length of the tube.

Lower V - block 142 is attached to moving table 184 of a translation stage or slide table 180. Translation stage 180 is a standard component commercially available from several vendors, and it provides for a smooth motion of moving table 184 which is precisely constrained to a straight line. Translation stage 180 consists of moving table 184 and a fixed base 182, connected by crossed roller bearing slides 186. Fixed base 182 is attached to a BPA baseplate 162.

The bearings in translation stage 180 could also be either ball bearings or a dovetail slide. Such stages are also commercially available, and are generally considered to be less precise than those using crossed roller bearings, though they do have advantages, including lower cost. Translation stage 180 could also be an air bearing stage, which may offer even more motion accuracy than does the crossed roller bearing version, although at a considerable increase in system cost and complexity.

Also attached to BPA baseplate 162 is a micrometer mounting block 166. Mounting block 166 supports a micrometer 168. Micrometer 168 has an extension shaft 170 , a rotating drum 178, and a distance scale 172. As drum 178 is rotated, a precision screw inside the micrometer rotates inside a precision nut, thus changing the distance between the end of extension shaft 170 and mounting block 166. Of course, micrometer 168 could be a digital unit, rather than the traditional analog unit shown.

Micrometer extension shaft 170 is connected to an actuator arm 174 through a bushing 176. Actuator arm 174 is mounted to moving table 184. Bushing 176 allows for a slight amount of non-parallel motion between micrometer extension shaft 170 and moving table 184, at the cost of allowing some backlash in the relative motions of table 184 and shaft 170. Micrometer scale 172 can be read to determine the position of moving table 184 within its range of motion.

Figure 6 shows a detailed view of bushing 176 and the interface between micrometer extension shaft 170 and actuator arm 174. Shaft 170 is captured within bushing 176 so that arm 174 will follow position changes of shaft 170 in either direction, with the previously mentioned small amount of backlash.

Figure 7 shows a block diagram of the electronic portion of this first embodiment. Figure 7 represents the electronics of a standard, known borescope video system except for the addition of a cursor controller 230 and a computer 228. In Figure 7, an illumination controller 200 is connected to the borescope through a fiber optic cable 206 as has previously been described. Video camera back 134 is connected to camera controller 212 through camera control cable 135 as has also been described. For the known system, the video signal out of the camera controller is connected to a video monitor 214 and, optionally, to a video recorder 216, through a video cable 137 as shown by the broken line in Figure 7. In this embodiment, the video signal from camera controller 212 is instead sent to cursor controller 230. The video signal as modified by cursor controller 230 is then supplied to video monitor 214 and to video recorder 216. Use of video recorder 216 is optional, though its use makes it possible for the user to repeat measurements or to make additional measurements at some later time, without access to the original measurement situation.

Figure 8 shows a view of the video monitor as seen by the user. On video screen 310 there is seen a circular image of the borescope field of view, which I call the *apparent field of view*, 312. Inside apparent field of view 312 is shown an image of the object under inspection 314. Superimposed on video screen 310, and hence on image 314, are a pair of cross-hairs, fiducial marks, or cursors, 316 (Cursor A) and 318 (Cursor B). These cursors can be moved to any portion of the video screen, and can be adjusted in length, brightness, and line type as required for best alignment with points of interest on image 314. Note that these cursors do not need to be cross-hairs; other easily discernible shapes could also be produced and be used as well.

The generation of video cursors is well known by those familiar with the art, so is not part of this invention.

The functions of cursor controller 230 are controlled by computer 228 (Figure 7). Computer 228 has a user interface that allows manipulation of the cursor positions as desired. It also provides a means for the user to indicate when a given cursor is aligned appropriately, so that an internal record of the cursor position can be made. It provides means for the user to input numerical data as read from micrometer scale 172. In addition, computer 228 contains software which implements algorithms to be described which combine these numerical data appropriately to derive the true three dimensional distance between points selected by the user. Finally, computer 228 provides a display means, whereby the distance(s) determined is (are) displayed to the user. Clearly, this display could be provided directly on video screen 310, a technology which is now well known, or it could be provided on the front panel or on a separate display screen of computer 228.

The system described by Konomura in US patent 5,575,754 is similar to mine in that it also allows one to move a borescope to various positions along a straight line path and to view and select points on the image of the object on a video screen. However, Konomura uses a cylinder sliding within a cylinder, driven by a rack and pinion, to do the positioning of the borescope. There are two basic problems with Konomura's positioning mechanism which are overcome in my system.

The first problem with Konomura's mechanism is that it is difficult and expensive to achieve an adequate accuracy of straight line travel with a cylinder sliding inside a cylinder as compared to the translation stage of my preferred embodiment, which is widely available at reasonable cost and which provides exceedingly accurate *motion*. The accuracy of the straight line motion directly affects the accuracy of the perspective measurement. The second problem is that Konomura's use of a rack and pinion to drive the position of the borescope means that that position will tend to slip if the borescope is not oriented exactly horizontal, due to the weight of the moving

assembly. Konomura makes no provision for holding the position of the borescope. With my micrometer drive, or more generally, with a lead screw drive, the high mechanical advantage means that there would be no tendency for the position to slip even if the lead screw were supporting the full weight of the moving assembly.

There are fundamental reasons why the translation stage or slide table of my preferred embodiment provides a more accurate straight line motion than does a cylinder sliding within a cylinder. First, the translation stage uses rolling friction rather than the sliding friction of Konomura's system. This means that there is much less tendency to alternating stick and slip motion ("stiction"). Secondly, the translation stage makes use of the principle of averaging of mechanical errors. The ways and rollers of slides 186 of stage 180 are produced to very tight tolerances to begin with. Then, the ways and rollers are heavily preloaded so that, for instance, any rollers that are slightly larger than the average undergo an elastic deformation as they roll along the ways. Thus, the motion of moving table 184 is determined by an average of the positions that would be determined by errors in the ways and the individual rollers. One cannot use a large preload to average out errors in a cylinder sliding within a cylinder, because then the friction would become too high. This is especially true because of the large surface contact area involved. I mentioned above that a dovetail slide could also be used in my system. Such a slide can be preloaded to average motion errors without the friction becoming too high simply because the surface contact area is suitably small.

C. Operation of the First Embodiment

The view of the object shown in Figure 8 has the problem that it is a two-dimensional projection of a three-dimensional situation. Clearly the combination of cursor controller 230 and computer 228 is capable of making relative measurements of the apparent size of features on object image 314, as is well known. But, because there is no information on distance, and because the distance may vary from point to point in the image, there is no way to determine the true dimensions of object feature 102 from image 314.

The solution offered by my perspective measurement system is to obtain a second view of the object as shown in Figure 9. This second view is obtained by translating video borescope 120 a known distance along an accurate straight line path using BPA 138 described above.

The following discussion of the operation of my system assumes that it is the distance between two points on the object which is to be determined. As will become clear, it is straightforward to extend the measurement process to as many points as desired. In the case of more than two points, the distances between all other points and one particular reference point could be determined by the process described below. Additionally, the distances between all of the points taken as pairs could be determined from the same data gathered during this process.

I will now outline a first mode of distance measurement operation. As was shown in Figure 8, to begin the process the borescope is aligned with the object to produce a view where the points of interest are located substantially on one side of the field of view. In that view, cursor A (316) and cursor B (318) are aligned with the two points of interest, respectively, as shown in Figure 8. When the cursors are aligned correctly, the user indicates this fact through the user interface of computer 228, and computer 228 records the locations of cursors A and B. The user also then enters the position of moving table 184 as indicated on micrometer distance scale 172.

Using micrometer 168, the user then repositions the borescope to obtain a second view of object 100. As shown in Figure 9, the user selects a second position of the borescope to bring the points of interest to substantially

the other side of the borescope field of view as compared to where they were in the first view. The cursors are then once again used to locate the positions of the points of interest, cursor A for point A and cursor B for point B. In Figure 9, Cursor B (318) is shown temporarily moved to an out of the way position to avoid the possibility of confusion when the user is aligning cursor A with Point A. The user has the option of aligning and recording the cursor positions one at a time, if desired. When the cursors are positioned correctly, or when each cursor is positioned, if they are being used one at a time, the user indicates that fact through the user interface of computer 228. The user then enters the new position of moving table 184 as indicated on micrometer distance scale 172.

With the data entered into computer 228, (two cursor position measurements for each point of interest and two borescope position measurements) the user then commands the computer to calculate and display the true three dimensional distance between the points which were selected by the cursors. The computer combines the measured data with calibration data to determine this distance in a software process to be described further below. The calibration data can be obtained either before the measurement or after the measurement, at the option of the user. In the latter case, computer 228 will store the acquired data for future computation of the measured distance. Also, in the case of post-measurement calibration, the user has the option of directing computer 228 to use preliminary or previously obtained calibration data to provide an approximate indication of the distance immediately after the measurement, with the final distance determination to depend on a future calibration.

The measurement process just outlined is that expected to be the one most generally useful and convenient. However, there is no requirement to use two separate cursors to determine the apparent positions of two points on the object, because one cursor would work perfectly well as long as the cursor position data for each point of interest are kept organized properly. In addition, it may be that the distances between more than a single pair of points is desired. In this case, there are just more data to keep track of and nothing fundamental has changed.

I now outline a second mode of distance measurement operation. Consider measurement of the distance between two points which are so far apart that both points cannot lie on substantially the same side of apparent field of view 312. Figures 10 and 11 show an example of this situation, where the three-dimensional distance between the two ends of an elliptical feature is to be determined. Figures 10A and 10B show the two steps involved in the determination of the three dimensional location of the first end of the elliptical feature. Figures 11A and 11B show the two steps involved in the determination of the three dimensional location of the second end of the elliptical feature. In this mode of distance measurement, a point of interest on the object is first brought to a location on one side of apparent field of view 312 and a cursor is aligned with it. The cursor position and micrometer position data are then stored. The view is then changed to bring the point of interest to the other side of apparent field of view 312, and the cursor position and micrometer position data are once again stored. This same process is carried out sequentially for each point of interest on the object. After all of the cursor and micrometer position data are gathered, the computer is instructed to calculate the desired distances between points.

Note that in this second mode of distance measurement operation, the two points of interest could be located so far apart that they could not both be viewed at the same time. In this case the measurement still could be made. That is, there is no requirement that the distance to be measured be completely containable within apparent field of view 312. The only limit is that two suitable views of each point be obtainable within the translation range of BPA 138. This is a capability of my system that was not conceived of in the prior art.

In detail, the process of making a measurement of the distance between two points, both of which are contained within a relatively small portion of apparent field of view 312 as shown in Figures 8 and 9, (I call this *measurement mode 1*) is made up of the following steps:

1. A specific area of interest on object image 314 is located in apparent field of view 312 by sliding and rotating borescope 120 inside borescope clamp 140.
2. Borescope clamp 140 is locked with clamping screw 150 to secure the position and orientation of the borescope with respect to BPA 138.
3. Micrometer drum 178 is rotated to select a first view of the object, with both points of interest located substantially on one side of apparent field of view 312, such as that shown in Figure 8. The approximate position of the micrometer as read from scale 172 is noted.
4. Micrometer drum 178 is rotated to select a second view of the object, such as that shown in Figure 9. This step insures that a suitable view is, in fact, obtainable within the range of motion of micrometer 168, and that, for instance, the view is not blocked by intervening objects.
5. Micrometer drum 178 is then rotated back again to approximately the position selected for the first view. At this point, the rotation of the micrometer is again reversed so that the micrometer is being rotated in the direction that is necessary to move from the first view to the second view. After a sufficient reverse rotation to ensure that the backlash of bushing 176 has been taken up, the micrometer rotation is halted. This is now the selected viewing position for the first view.
6. Cursors 316 and 318 are then aligned with the selected points on object image 314 using the user interface provided by computer 228.
7. When each cursor is aligned correctly, computer 228 is commanded to store the cursor positions. The cursors can be aligned and the positions stored either sequentially, or simultaneously, at the option of the user.
8. The user reads micrometer scale 172 and enters the reading into the computer with the user interface provided.
9. Micrometer drum 178 is now carefully rotated in the direction necessary to move from the position of the first view to the position of the second view. This rotation stops when the user judges the second view to be satisfactory for the purposes of the measurement desired, such as that shown in Figure 9.
10. The user repeats steps 6, 7, and 8.
11. The user commands the computer to calculate and display the true three-dimensional distance between the points selected by the cursors in steps 6 and 10. If desired, the computer can be commanded to also display the absolute positions of each of the two points. These absolute positions are defined in a coordinate system to be described below.

In detail, the process of making a measurement of the distance between two points, when they cannot both be contained within a relatively small portion of the apparent field of view 312 as shown in Figures 10 and 11, (I call this *measurement mode 2*) is made up of the following steps:

1. Computer 228 is instructed to command cursor controller 230 to produce a single cursor. While it is not absolutely necessary to use a single cursor, I believe that the use of a single cursor helps avoid unnecessary confusion on the part of the user.
2. The user adjusts micrometer 168 to approximately the midpoint of its range by rotating drum 178.
3. A specific area of interest on object image 314 is located in apparent field of view 312 by sliding and rotating borescope 120 inside borescope clamp 140. The two points of interest are identified, and the borescope is positioned so that the center of apparent field of view 312 is located approximately equidistant between the two points of interest.
4. Borescope clamp 140 is locked with clamping screw 150 to secure the position and orientation of the borescope with respect to BPA 138.
5. Micrometer drum 178 is rotated to select a first view of the first point of interest. The first view is selected so that the point of interest is located substantially on one side of apparent field of view 312, such as that shown in Figure 10A. The approximate position of the micrometer as read from scale 172 is noted.
6. Micrometer drum 178 is rotated to select a second view of the first point. The second view is selected so that the point of interest is located substantially on the other side of apparent field of view 312 from where it was in the first view, such as that shown in Figure 10B. This step insures that a suitable view is, in fact, obtainable within the range of motion of micrometer 168, and that, for instance, the view is not blocked by intervening objects.
7. Steps 5 and 6 are repeated for the second point of interest, as depicted in Figures 11A and 11B. This step ensures that suitable views are, in fact, obtainable for the second point of interest with the borescope alignment chosen in step 3.
8. Micrometer drum 178 is then rotated to approximately the position selected for the first view of the first point of interest (Step 5). At this point, the user makes sure that the micrometer is being rotated in the same direction that is necessary to move from the first view to the second view of the first point of interest. After a sufficient rotation to ensure that the backlash of bushing 176 has been taken up, the micrometer rotation is halted. This is now the selected position for the first view of the first point of interest.
9. The cursor is then aligned with the first point of interest on object image 314 using the user interface provided by computer 228.
10. When the cursor is aligned correctly, computer 228 is commanded to store the cursor position.
11. The user reads micrometer scale 172 and enters the reading into the computer with the user interface provided.
12. Micrometer drum 178 is now carefully rotated in the direction necessary to move from the position of the first view to the position of the second view. This rotation stops when the user judges the second view to be satisfactory for the purposes of the measurement desired.
13. The user repeats steps 9, 10, and 11.
14. Micrometer drum 178 is rotated to obtain the first view of the second point of interest, which was selected during step 7. The user repeats step 8 for this first view of the second point of interest.

15. The user repeats steps 9 to 13 for the second point of interest.
16. The user commands the computer to calculate and display the true three-dimensional distance between the points. If desired, the computer can be commanded to also display the absolute positions of each of the two points, in the coordinate system to be defined below.

I have repeatedly emphasized that the user should position the points of interest first near one edge of apparent field of view 312, then near the other edge, during the measurement. The reason is that analysis of the errors in the measurement shows that there is, in general, an optimum perspective baseline to be used, and that this optimum baseline differs for each individual measurement. The primary requirement on the perspective baseline is that it be chosen to be proportional to the range of the object from the camera. A secondary, and less important, requirement is that the perspective baseline be chosen to correspond to an optimum measurement viewing angle of the borescope being used. While the exact optimum measurement viewing angle depends on the detailed characteristics of the borescope, for most borescopes the optimum angle will be somewhere near the edge of the field of view, although not exactly at the edge. Use of the procedure as specified above automatically ensures that both of these requirements on the perspective baseline are being achieved for the particular measurement being attempted.

It should be clear that the measurement process and mechanical hardware I have defined could be used with borescopes other than video borescope 120 as I have described it. For instance, the video borescope could be implemented with a tiny video camera and lens located at the distal end of a rod or tube without changing this system of measurement at all. In such an "electronic borescope" there would be no need of a lens train to conduct the image from the distal end to the proximal end. While flexible electronic endoscopes built this way are currently available, I am not aware of a rigid borescope like this. However, when one considers that optical components keep getting more expensive while solid state imagers keep getting less expensive and that the resolution of solid stage imagers keeps increasing, it seems likely that electronic borescopes will be used at some future time, especially in the longer lengths, where the optical performance of ordinary borescopes is degraded. (I will later describe an electronic measurement borescope; here I am speaking of an electronic borescope that contains no inherent measurement capability.)

This system could also be used with a visual borescope, that is, one with no video at all, requiring only that the borescope eyepiece contains an adjustable fiducial mark with a position readout (a device commonly called a "filar micrometer"). Such an embodiment of the system, while feasible, would have the strong disadvantage of requiring the manual transcription of fiducial position data, which would be a source of errors. It also would have the disadvantage of requiring the user to perform a delicate and precise task, namely accurately aligning the fiducial mark with a selected point on the image of the object, while under the physical stress of looking through the borescope. (In general the borescope would be located at a position awkward for the user). And, of course, such a visual measurement borescope would not be a standard component, unlike the video borescope I have discussed.

It is also clear that the video system could be a digital video system as well as the analog system I have discussed. That is, the video signal could be digitized into discrete "pixels" with a video "frame grabber" and all video processing could be done digitally. Konomura's system is implemented with digital video. Such systems are

more expensive than my simple analog system, and there is another disadvantage that is more subtle, but is important.

A detailed analysis shows that the perspective measurement process is much more sensitive to errors made in locating the image point in the direction of the perspective displacement than in the direction perpendicular to the perspective displacement. This means that for best measurement accuracy, one wants to arrange the system so that the smallest feasible errors are made along the direction of the perspective displacement as projected onto the image plane. For standard video systems there is a difference in resolution between the horizontal and vertical video directions, with the horizontal direction having the higher resolution. This higher resolution applies not only to the video sensor itself, but also to the cursor position resolution.

In a digital system, the horizontal cursor resolution is limited by the number of horizontal pixels in each line of video, which is typically about 512 or certainly no more than 1024 for a standard system. In an analog system, the horizontal cursor resolution is not limited to any particular value, since it is a matter of timing. It is straightforward to build an analog cursor positioning system which provides a cursor resolution of nearly 4000 positions across the video field. This higher horizontal cursor resolution available to my analog system is valuable in minimizing the error in the measurement.

As I previously mentioned, the prior art perspective measurement assumes that the viewing camera optical axis is oriented perpendicular to the perspective displacement, that is, along the z axis in Figure 2. It also assumes that the horizontal and vertical axes of the camera are oriented along the x and y directions in that Figure. Clearly, in view of Figures 1 and 4, these assumptions are not adequate if one wants to use any substantially side-looking borescope without any specific alignment between the optical axis and the centerline of the borescope or without any specific rotational orientation of video camera back 134 with respect to field of view 122.

Because of the higher available resolution in the horizontal video direction, one wants to arrange things so that the perspective displacement is viewed along the horizontal video direction. Thus, in order to achieve the most precise measurements possible with my system, the user should prepare the borescope before making measurements by rotating video camera back 134 about the axis of borescope 120 so that the horizontal video direction of camera back 134 is approximately aligned to the plane in which the optical axis of field of view 122 lies. (This assumes that there is no additional rotation of the image about the optical axis inside the borescope. If there is such an additional rotation, then one rotates the camera back to align the horizontal video direction with the projected direction of the perspective displacement as seen at the position of the video sensor.)

This alignment will ensure that measurements are made with the smallest feasible random error. But, in order to obtain the random error reducing properties of this alignment, it is not necessary that it be very accurate. Thus, this preparatory alignment is not a formal part of the measurement procedure, nor of the calibration of the system, which is discussed later. In any case, whether this preparatory alignment is performed or not, my calibration procedure determines the actual alignment of the camera, and my data processing procedure takes that alignment correctly into account in the measurement.

In the measurement processes that were described above, the experimental data obtained are four image position coordinates $(x'_{im1}, y'_{im1}, x'_{im2}, y'_{im2})$ for each object point of interest and the reading of the micrometer at

each viewing position. I now explain how to combine these measured quantities, together with calibration data, in an optimum way to determine the distance between the two points of interest.

Figure 12 shows a generalized perspective measurement situation. Here, two viewing coordinate systems are set up, each of which is determined by the x and y axes of the camera focal plane, and their mutual perpendicular $\hat{z} = \hat{x} \times \hat{y}$.

In Figure 12 a first coordinate system has its origin at the first observation point, P1, and a second coordinate system has its origin at the second observation point, P2. Because there may be a rotation of the camera in moving between P1 and P2, the coordinate axes at P1 and P2 are not parallel, in general. These coordinate systems are denoted by the subscripts 1 and 2. That is, the P1 coordinates of a point are expressed as (x_1, y_1, z_1) while the coordinates of the same point, as expressed in the P2 system, are (x_2, y_2, z_2). The P2 coordinate system has its origin at $\mathbf{d}$ in the P1 system.

To accomplish the perspective measurement, the arbitrary point P_i is viewed first in the P1 coordinate system, then in the P2 coordinate system.

Because in this first embodiment I use a translation stage which provides a high degree of precision in the motion of the camera, I assume for now that there is no rotation of the camera in the translation between P1 and P2. In this case, the coordinate axes of the two systems in Figure 12 are parallel. The partial generalization here is that the perspective displacement between P1 and P2, $\mathbf{d}$, can be at any arbitrary orientation with respect to the viewing coordinate axes.

In the discussion of the prior art above, the following relationships between the camera image plane coordinates and the corresponding object point coordinates were determined:

$$x_{im} = -\frac{i\,x}{z} \;;\; y_{im} = -\frac{i\,y}{z} \tag{9}$$

where i is the distance from the nodal point of the optical system to the image plane. Similar equations hold for the observations at both camera positions. These image point data can be written in vector form as:

$$\mathbf{r}_{im} = \begin{bmatrix} x_{im} \\ y_{im} \\ z_{im} \end{bmatrix} = \begin{bmatrix} x_{im} \\ y_{im} \\ -i \end{bmatrix} = -\frac{i}{z}\begin{bmatrix} x \\ y \\ z \end{bmatrix} = -\frac{i}{z}\,\mathbf{r} \tag{10}$$

or

$$\mathbf{r} = -\frac{z}{i}\,\mathbf{r}_{im} = z\begin{bmatrix} -\frac{x_{im}}{i} \\ -\frac{y_{im}}{i} \\ 1 \end{bmatrix} = z\,\mathbf{a}_v \tag{11}$$

The vector $\mathbf{a}_v$, which I call the *visual location vector*, contains the image point location data for the measurement of the apparent location of a point P_i from a given viewing position. These data, of course, are assumed to have been corrected for camera distortion as was previously explained and will be discussed in detail later. The distance, z, is unknown. When one measures the apparent locations of P_i from two viewing positions, separated by a vector $\mathbf{d}$, one has two vector equations:

$$\begin{aligned} \mathbf{r}_1 &= \mathbf{r}_2 + \mathbf{d} = z_2\,\mathbf{a}_{v2} + \mathbf{d} \\ \mathbf{r}_1 &= z_1\,\mathbf{a}_{v1} \end{aligned} \tag{12}$$

where $\mathbf{r}_1$ is the location of a point as expressed in the coordinate system which has its origin at P1, and $\mathbf{r}_2$ is the location of the same point as expressed in the coordinate system tied to P2.

Expressions (12) represent 6 equations 4 unknowns. The four unknowns are the three components of $\mathbf{r}_1$ (or $\mathbf{r}_2$) and z_2 (or z_1).

Subtracting the two Equations (12), one obtains:

$$z_1\,\mathbf{a}_{v1} - z_2\,\mathbf{a}_{v2} = \mathbf{d} \tag{13}$$

which can be written as a matrix equation:

$$[\mathbf{a}_{v1} \quad -\mathbf{a}_{v2}]\begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = \mathbf{d} \tag{14}$$

Expression (14) represents three equations in two unknowns. When there are more equations than unknowns, the system of equations is called over - determined, and there is in general no exact solution. However, because the coefficients of the equations are experimentally determined quantities that contain noise, one wouldn't want an exact solution, even if one happened to be available. What one wants is a solution that "best fits" the data in some sense. The standard criterion for "best" is that the sum of the squares of the deviations of the solution from the measured data is minimized. This is the so-called <u>least squares</u> solution or *least squares estimate*.

The least squares solution of the over determined system of Equations (14) can be simply expressed by introducing the left pseudo-inverse of the data matrix:

$$\begin{bmatrix} z_1 \\ z_2 \end{bmatrix} = [\mathbf{a}_{v1} \quad -\mathbf{a}_{v2}]^{LI}\,\mathbf{d} \tag{15}$$

Adding the two Equations (12), one obtains:

$$2\,\mathbf{r}_1 - \mathbf{d} = [\mathbf{a}_{v1} \quad \mathbf{a}_{v2}]\begin{bmatrix} z_1 \\ z_2 \end{bmatrix} \tag{16}$$

Substituting (15) into (16):

$$\mathbf{r}_1 = \frac{1}{2}\Big[[\mathbf{a}_{v1} \quad \mathbf{a}_{v2}][\mathbf{a}_{v1} \quad -\mathbf{a}_{v2}]^{LI} + \mathbf{I}_3\Big]\mathbf{d} \tag{17}$$

where $\mathbf{I}_3$ is the identity matrix of dimension 3. Equation (17) gives a three-dimensional least squares estimate for the location of the point of interest, P_i, as expressed in the coordinate system at viewing position P1, for the visual location vectors $\mathbf{a}_{v1}$ and $\mathbf{a}_{v2}$ measured at viewing positions P1 and P2 respectively.

To aid in the comparison of expressions (17) to the prior art result (6), introduce an auxiliary coordinate system into expression (17). Recall that (6) refers to a coordinate system which is defined such that the origin lies exactly half way between the two observation positions. Therefore, define:

$$\mathbf{r}_m = \mathbf{r}_1 - \frac{1}{2}\,\mathbf{d} \tag{18}$$

Then:

$$\mathbf{r}_m = \frac{1}{2}[\mathbf{a}_{v1} \quad \mathbf{a}_{v2}][\mathbf{a}_{v1} \quad -\mathbf{a}_{v2}]^{LI}\,\mathbf{d} \tag{19}$$

This is the simple, general expression for the location of a point of interest, given experimentally determined

apparent positions, when the perspective displacement **d** is oriented in some arbitrary direction. Expression (19) is correct and complete as long as the motion of the camera between the two viewing positions is a pure translation.

An important conclusion from expression (19) is that the determination of the position of a point, **r**, from the measured data requires only the knowledge of the perspective displacement vector **d**, as expressed in the P1 coordinate system, and the image distance or effective focal length, i (from (11)). Of course, the image point position data incorporated in visual location vectors $\mathbf{a}_{v1}$ and $\mathbf{a}_{v2}$ must have been corrected for the distortion of the optical system before being used in (19), as was previously explained.

To compare (19) to the prior art result, note that the left pseudo-inverse of a matrix can be written as:

$$\mathbf{A}^{LI} = (\mathbf{A}^T\mathbf{A})^{-1}\mathbf{A}^T \tag{20}$$

and specify that **d** is directed along the x axis, as was assumed in the derivation of (6). When one also assumes that $y_{im1} = y_{im2}$, one finds that (19) reduces to:

$$\mathbf{r}_m = \frac{d}{2(x_{im2} - x_{im1})}\begin{bmatrix} -(x_{im1} + x_{im2}) \\ -2\,y_{im1} \\ 2\,i \end{bmatrix} \tag{21}$$

Clearly, (21) is identical to (6) for the case where $y_{im1} = y_{im2}$.

The optimum way to use the four measurements, according to the least squares criterion, is given by (19). It reduces to result (21) for the case where **d** is directed along the x axis and when the two images are located at the same y positions. If the measured y_{im1} does not equal y_{im2} but the difference is small, it can be shown that the least squares result is the same as using the average value of y_{im1} and y_{im2} in (21) in place of y_{im1} (but only when **d** is directed along the x axis).

Now consider measurement mode 1. Assume that two points of interest, A and B, are viewed from two camera positions, P1 and P2.

The distance between P1 and P2 is d, and is simply calculated from the experimental data as $d = l_2 - l_1$, where l_1 and l_2 are the micrometer readings at viewing positions P1 and P2 respectively. Considering now the determination of the location of either one of the points, one next corrects the measured image position data for distortion. As I discuss further in the calibration section, I use the term *distortion* to refer to any deviation of the image position from the position that it would have if the camera were perfect. This is a much more general definition than is often used, where the term refers only to a particular type of optical field aberration.

Of course, this distortion correcting step is performed only if the distortion is large enough to affect the accuracy of the measurement, but this will be the case when using any standard borescope or almost any other type of camera to perform the perspective measurement.

As is further described in the calibration section, one can write the image position coordinates as:

$$\begin{aligned} x_{im} &= x'_{im} - f_{Dx}(x'_{im}, y'_{im}) \\ y_{im} &= y'_{im} - f_{Dy}(x'_{im}, y'_{im}) \end{aligned} \tag{22}$$

where (x'_{im}, y'_{im}) are the experimental measurements and (x_{im}, y_{im}) are the distortion corrected versions. The same equation applies to the data at both camera positions, that is, both x'_{im1} and x'_{im2} are subjected to the same correction function f_{Dx} and both y'_{im1} and y'_{im2} are corrected with f_{Dy}. The distortion correction functions f_{Dx} and

f_{Dy} are determined in a calibration process which is described in the calibration section. This calibration process is known in the art.

Next, the data are scaled by the inverse of the effective focal length of the combined optical-video system. That is, the data $(x_{im1}, y_{im1}, x_{im2}, y_{im2})$ are multiplied by a factor necessary to generate the equivalent true values of the tangent of the viewing angles:

$$\begin{aligned} \tan(\alpha_{x1}) &= -\frac{x_{im1}}{i} \\ \tan(\alpha_{y1}) &= -\frac{y_{im1}}{i} \end{aligned} \qquad (23)$$

and likewise for the other two measurements for this point on the object from position P2. The equivalent focal length, i, is preferably determined in the same calibration process as is the distortion, as will be described later in the calibration section.

Next two visual location vectors are formed from the scaled, distortion corrected image position measurements. These vectors are :

$$\mathbf{a}_{v1} = \begin{bmatrix} \tan(\alpha_{x1}) \\ \tan(\alpha_{y1}) \\ 1 \end{bmatrix} \text{ and } \mathbf{a}_{v2} = \begin{bmatrix} \tan(\alpha_{x2}) \\ \tan(\alpha_{y2}) \\ 1 \end{bmatrix} \qquad (24)$$

The perspective displacement is formed by placing the perspective baseline (the measured distance between viewing positions P1 and P2) as the first element of a vector:

$$\mathbf{d}_b = \begin{bmatrix} d \\ 0 \\ 0 \end{bmatrix} \qquad (25)$$

The perspective displacement is then transformed to the viewing coordinate system defined by the camera at P1 by multiplication of $\mathbf{d}_b$ by a pair of 3 x 3 rotation matrices $\mathbf{R}_y$ and $\mathbf{R}_z$:

$$\mathbf{d}_{v1} = \mathbf{R}_z \mathbf{R}_y \mathbf{d}_b \qquad (26)$$

The multiplications in Equation (26) are standard matrix multiplications of, for instance, a 3 x 3 matrix with a 3 x 1 vector. Rotation matrices $\mathbf{R}_y$ and $\mathbf{R}_z$ describe the effects of a rotation of the coordinate system about the y axis and about the z axis respectively. They are each defined in a standard way as a function of a single rotation angle. The definitions of the rotation matrices, and the calibration process for determination of the rotation angles, are given later. The alignment calibration process that I define there to determine these rotation angles is new.

The location of the point being determined is then calculated according to Equation (19) as:

$$\mathbf{r}_m = \begin{bmatrix} x \\ y \\ z \end{bmatrix} = \frac{1}{2}[\mathbf{a}_{v1} \quad \mathbf{a}_{v2}][\mathbf{a}_{v1} \quad -\mathbf{a}_{v2}]^{LI}\mathbf{d}_{v1} \qquad (27)$$

The process ending with the calculation expressed in Equation (27) is performed for the data obtained on points A and B in turn, and then Equation (7) is used to calculate the desired distance between points A and B.

Measurement mode 2 is depicted in Figure 13. Here there are up to a total of four viewing positions used. The fields of view of the camera at each position are indicated by the solid lines emanating from the viewing

position, while the camera optical axes are denoted by the dot-dash lines. Dashed lines indicate schematically the angles at which points A and B are viewed from each position.

Because of the accurate motion provided by translation stage 180, the viewing positions all lie along a straight line and the viewing coordinate systems are all parallel. Figure 13 is drawn as the projection of a three-dimensional situation onto the x, z plane of the camera. Thus, the viewing positions and the line along which they are drawn do not necessarily lie in the plane of the Figure, nor do the points of interest A and B.

Point of interest A is viewed from positions P1A and P2A with perspective baseline d_A, while point B is viewed from P1B and P2B with perspective baseline d_B. The experimental data obtained during the mode 2 measurement process are the four image point coordinates for each of the points A and B, and the four viewpoint positions along the camera motion axis l_{1A}, l_{2A}, l_{1B}, and l_{2B}. Note that two of the viewing positions could be coincident, so that a total of three different viewing positions would be used, and this mode would still be distinct from mode 1.

Vectors $\mathbf{r}_A$ and $\mathbf{r}_B$ are determined using the perspective baselines $d_A = l_{2A} - l_{1A}$ and $d_B = l_{2B} - l_{1B}$ as has just been described for measurement mode 1. The distance between the coordinate origins for the measurements of A and B is then calculated as:

$$d_{AB} = \frac{1}{2}(l_{1A} + l_{2A} - l_{1B} - l_{2B}) \tag{28}$$

Next, vector $\mathbf{d}_{AB}$ in the camera coordinate system is calculated as:

$$\mathbf{d}_{AB} = \mathbf{R}_z \mathbf{R}_y \begin{bmatrix} d_{AB} \\ 0 \\ 0 \end{bmatrix} \tag{29}$$

Finally, the desired distance between points A and B, r, is calculated as:

$$r = |\mathbf{r}| = |\mathbf{d}_{AB} + \mathbf{r}_A - \mathbf{r}_B| = \sqrt{\mathbf{r}^T\mathbf{r}} \tag{30}$$

where the vertical lines indicate the magnitude (length) of a vector.

Measurement mode 2 can have a lower random error than does measurement mode 1 because the points of interest can be brought to the optimum apparent angular position in each of the views, whereas the apparent angular positions chosen for the points in measurement mode 1 is necessarily a compromise.

In contrast to the prior art, my data processing procedure correctly takes into account the general geometry of the perspective measurement. Because of this, it is possible to define a complete set of parameters which can be calibrated in order to obtain an accurate measurement no matter what measurement geometry is used. Thus, it is only my measurement system which can make an accurate measurement with a standard, off the shelf, video borescope. In addition, I make use of all of the available measurement data in an optimum way, to produce a measurement with lower error than otherwise would be provided. Finally, my system provides a new measurement mode (mode 2) which allows one to measure objects which are too large to be measured with prior art systems, and which provides the lowest feasible random measurement error.

D. Description of a Second Embodiment

Figure 14 shows a block diagram of the electronic portion of a second embodiment of my system. The new elements added as compared to the first embodiment are a position transducer 360, a motion actuator 410, a

motion controller 452 and a position measurement block 470. The latter two blocks are combined with cursor controller 230 and computer 228 into a block called the system controller 450. Position transducer 360 is connected to position measurement block 470 by a position transducer cable 366. Motion actuator 410 is connected to motion controller 452 with an actuator cable assembly 428.

This second embodiment of the electronics could be built with the capability of completely automatic operation of the position of borescope 120. That is, borescope 120 could be positioned anywhere within the range of travel of translation stage 180 (Figure 5) under control of computer 228 upon operator command. In this case, the user would only have to command some initial position for translation stage 180, then align and clamp borescope 120 appropriately as described above for the operation of the first embodiment, and then never have to touch any of the mechanical hardware again during the measurement process. The two viewing positions, P1 and P2, as described previously, would be selected by the user by moving stage 180 under computer control.

Such automatic positioning of borescope 120 could be closed-loop positioning. That is, the computer would position the borescope by moving the borescope until a particular desired position was indicated by the combination of transducer 360 and position measurement block 470.

In fact, the same commercial vendors who supply translation stages often supply complete positioning systems which combine a translation stage with the motion control and position measurement blocks shown in Figure 14. Most often these systems use an actuator comprising an electric motor, either a dc motor or a stepping motor, driving a precision lead screw. That is, the actuator is essentially a motorized micrometer. Clearly, there are a number of different actuators and position transducers that can be used in any such system.

What I consider the best mode for implementing this second embodiment of the invention is somewhat different than the system I have just described. I believe that a system can be built at lower cost and be at least as convenient to operate if it is built as I will now describe. Since the primary use of the mechanical subsystem is to move borescope 120 (Figure 4) back and forth between two positions, this embodiment is directed toward making that process simple and quick. Generally speaking, it takes a long time for a motor driven translation stage to move between positions spaced a significant distance apart.

The second embodiment of BPA 138 is shown in Figures 15 through 19. Figure 15 is a front view, Figure 16 is a top view, Figure 17 is a rear view, while Figures 18 and 19 are left and right side views respectively.

The same borescope clamp assembly 140 as was used in the first embodiment is also used in this second embodiment. As before, lens tube 124 has been removed from clamp 140 in these views for clarity. Clamp 140 is comprised of a lower V - block 142, an upper V - block 144, a hinge 148, and a clamping screw 150. The upper V - block is lined with a layer of resilient material 146, for the same reason given in the description of the first embodiment.

Also, just as in the first embodiment, lower V - block 142 is attached to the moving table 184 of a translation stage or slide table 180. The translation stage consists of a moving table 184 and a fixed base 182, connected by crossed roller bearing slides 186. Fixed base 182 is attached to a BPA baseplate 162.

The differences between this second embodiment of BPA 138 and the first embodiment are contained in the methods by which moving table 184 is positioned and how its position is determined. In this second embodiment an air cylinder 412 is mounted to an actuator mounting bracket 422 which is in turn mounted to baseplate 162. Air cylinder 412, which is shown best in Figure 18, has two air ports 420 and an extension rod 418. Air hoses (not

shown) are connected to ports 420 and are contained within actuator cable assembly 428 which was shown on the block diagram, Figure 14. The air hoses convey air pressure from motion controller 452 (Figure 14). Extension rod 418 is connected to an actuator attachment bracket 424 through an actuator attachment bushing 426. Bracket 424 is fastened to moving table 184 as is best shown in Figures 16 and 17.

On the other side of the moving table / borescope clamp assembly from air cylinder 412 is mounted a linear position transducer 360. Position transducer 360 consists of a linear scale body 362 and a scale read head 364, which are attached to each other as an integral assembly, but which are free to move with respect to one another within limits along one direction. Attached to read head 364 is a position transducer cable 366 which connects to system controller 450 as was shown in Figure 14. Scale body 362 is mounted to moving table 184 through a scale body mounting bracket 363. Read head 364 is mounted to BPA baseplate 162 through a read head mounting bracket 365.

Attached to the upper side of actuator attachment bracket 424 is a dovetail slide 404. Mounted on dovetail slide 404, as best shown in Figures 16 and 18, is an adjusting nut bracket 394. Bracket 394 contains a fixed nut 396 which in turn contains an adjusting screw 398. Adjusting screw 398 has an adjusting screw knob 400 and an adjusting screw tip 402 disposed at opposite ends of its length. Bracket 394 also contains a bracket position locking handle 406. Locking handle 406 is connected to a locking cam 407 mounted inside bracket 394. Locking cam 407 is shown only in Figure 17.

Dovetail slide 404 and adjusting nut bracket 394 and the items contained therein form a subassembly known as the forward stop positioner 390. An exactly similar assembly called the rearward stop positioner 388 is mounted to the BPA baseplate behind translation stage fixed base 182. Rearward stop positioner 388 is best shown in Figures 16, 17 and 19.

Depending on the position of moving table 184, adjusting screw tip 402 of adjusting screw 398 of forward stop positioner 390 can contact end stop insert 393 of end stop 392 as best shown in Figures 16 and 18. Similarly, the rearward stop positioner 388 is aligned so that the tip of its adjusting screw can contact the rear end of moving table 184, as can be best visualized from Figures 16 and 17.

In Figure 16 is shown a stop pin hole 440, the purpose of which will be explained below.

Although the overall length of BPA 138 could be made shorter if read head 364 were mounted to moving table 184 and scale body 362 were mounted to baseplate 162, I have chosen to mount the unit as shown because then cable 366 does not move with table 184. Either way will work, of course.

E. Operation of the Second Embodiment

As stated above, the differences between this second embodiment and the first embodiment relate to how the borescope is moved and how the position of the borescope is determined.

The inclusion of position transducer 360 and position measurement block 470 as shown in Figure 14 means that the user of the instrument is no longer responsible for making position readings and transcribing them into computer 228. When the user indicates that the cursors are positioned as desired, as was described in the operation of the first embodiment, the computer will now automatically command a camera position measurement from position measurement block 470 and will automatically store this datum.

Note that position transducer 360 need not be an absolute encoder of position. From Equation (28) (and the similar expression for measurement mode 1, which is not a display equation) it is clear that the measurement depends only on the distance moved between viewing positions. A constant value can be added to the encoded position without changing the measurement in any way. Thus, position transducer 360 together with position measurement block 470 need only produce a position value that has an offset which is constant over the period of a measurement. This offset need not be the same from measurement to measurement. This means that transducer 360 can be what is called an incremental distance encoder, and this is what will be described.

As I will explain later with regard to other embodiments, if one wants to correct for errors in the camera motion, or if one wants to use a camera motion that is not constrained to a perfect straight line, then it is necessary to know the absolute position of the camera with respect to some fixed reference point. The distance encoder that I describe here has what is known as a "home" position capability. The home position allows one to use the incremental encoder as an absolute encoder when and if required.

Position transducer 360 contains a precision magnetic or optical pattern formed on a plate inside scale body 362. Read head 364 reads the pattern and thereby produces signals which change according to changes in relative position between read head 364 and scale body 362. The unit depicted here is sold by RSF Elektronik Ges.m.b.H. of Tarsdorf, Austria, but similar units are available from Renishaw plc of the United Kingdom and Dr. Johannes Heidenhain GmbH of Germany. The unit shown is available in resolutions as small as 0.5 micrometer (μm), with guaranteed positioning accuracy as good as $\pm$ 2 μm over a length of 300 millimeters. For the short length unit used in the BPA, one would expect the accuracy to be considerably better.

Position measurement block 470 interprets the signals from read head 364 to determine changes in the position of read head 364 with respect to the scale inside scale body 362. Position measurement block 470 formats the position data into a form that is understood by computer 228. If the home position capability has not been used, then measurement block 470 will report a position relative to the position that the transducer assembly was in when the power was turned on. If the home capability has been used, then the position will be reported relative to the fixed home position. Whether the home position capability is used or not is a design decision which depends on whether motion errors are to be corrected. The method of correction for errors in the motion is discussed at length below in a sub-section entitled "Operation of Embodiments Using Arbitrary Camera Motion".

The existence of motion actuator 410 and motion controller 452 means that the user is not required to manually move the borescope between P1 to P2. This has the advantage of eliminating any chance that the user will accidentally misalign BPA 138, hence borescope 120, during the measurement process. It also has the advantage of eliminating the tedious rotation of the micrometer barrel 178 which is required during operation of the first embodiment.

Air cylinder 412 is a double action unit, which means that air pressure applied to one of the ports 420 will extend rod 418 while air pressure applied to the other port will retract rod 418. When a differential pressure is applied between the ports, rod 418 will move until it is stopped by some mechanical means. If there is no other mechanical stop, rod 418 simply moves to either its fully extended or fully retracted position.

Through the action of bushing 426 and attachment bracket 424, moving table 184 is constrained to move with extension rod 418. The extent of motion of table 184 is controlled by the mechanical stops created by the combination of forward stop positioner 390 and end stop 392 and the combination of rearward stop positioner 388

and the rear end of moving table 184. For instance, in the forward motion direction, the limit to the motion of table 184 is determined when adjusting screw tip 402 of adjusting screw 398 contacts insert 393 of end stop 392. Since the limit positions of table 184 are determined by these mechanical stops, backlash in bushing 426 does not affect the accuracy or repeatability of this positioning. Thus, viewing positions P1 and P2 are solely determined by the position of these mechanical limit stops. The measurement of these positions, however, is subject to any backlash contained within position transducer 360, or within the attachments of the transducer to the remainder of the structure.

Considering now the forward stop positioner 390, operating handle 406 rotates cam 407 to either produce or remove a locking force due to contact between cam 407 and dovetail slide 404. Thus, when unlocked, bracket 394 can be slid back and forth along dovetail slide 404 until adjusting screw tip 402 is located to give the desired stop position. Handle 406 is then rotated to force cam 407 against slide 404 to lock bracket 394 in place. Adjusting screw 398 can then be rotated in fixed nut 396 with handle 400 to produce a fine adjustment of the stop position.

Once the positions of adjusting screws 398 of forward stop positioner 390 and rearward stop positioner 388 are set as appropriate for the desired perspective viewing positions P1 and P2, moving back and forth between these positions is a simple matter of reversing the differential pressure across air cylinder 412. Depending on the length of the air hoses which connect cylinder 412 to motion controller 452, the characteristics of air cylinder 412, and the mass of the assembly being supported by moving table 184, it may be necessary to connect a motion damper or shock absorber (not shown) between moving table 184 and BPA baseplate 162. This would be required if it is not possible to control the air pressure change to produce a smooth motion of table 184 between the stops at P1 and P2.

Stop pin hole 440 is used as follows. At the beginning of the measurement process, it makes sense to start with moving table 184 centered in its range of travel. Therefore, a stop pin (not shown) is inserted into hole 440 and computer 228 is instructed to cause motion controller 452 to apply air pressure to cylinder 412 to produce an actuation force which will cause moving table 184 to move backwards until it is stopped by the stop pin. At this point the user is ready to begin the measurement set up process.

If the home positioning capability of transducer 360 is to be used, after the instrument is powered up, but before measurements are attempted, computer 228 is instructed by the user to find the home position. Computer 228 then commands motion controller 452 to move actuator 410 back and forth over its full range of motion. Computer 228 also commands position measurement block 470 to simultaneously look for the home position signature in the output signal from transducer 360. Once the home position is found, the offset of the position output data from position measurement block 470 is set so that a predetermined value corresponds to the fixed home position.

In detail, the process of making a measurement of the distance between two points, both of which are contained within a relatively small portion of apparent field of view 312 as shown in Figures 8 and 9, (that is, measurement mode 1) is made up of the following steps in this second embodiment:

1. Translation stage 180 is centered in its range of travel by use of a stop pin as described above.
2. A specific area of interest on object image 314 is located in apparent field of view 312 by sliding and rotating borescope 120 inside borescope clamp 140.
3. Borescope clamp 140 is locked with clamping screw 150 to secure the position and orientation of the borescope with respect to BPA 138.

4. Computer 228 is instructed to remove any differential air pressure across air cylinder 412. The stop pin is removed from hole 440. Moving table 184 is now free to move. The user moves table 184 rearward until the view on video screen 310 is approximately as shown in either Figure 8 or Figure 9.
5. Rearward stop positioner 388 is positioned so that the adjusting screw tip contacts the rear end surface of moving table 184. Stop positioner 388 is then locked at this position.
6. The user moves table 184 forward until the view on video screen 310 is approximately as shown in the opposite view of Figures 8 and 9. That is, if in step 4, the view in Figure 9 was attained, then in this step, the view in Figure 8 is to be obtained.
7. Forward stop positioner 390 is adjusted so that the adjusting screw tip contacts end stop insert 393, and is then locked into position.
8. The computer is instructed to apply air pressure to move table 184 rearward. The view on video screen 310 is inspected and any fine adjustments to the position of the borescope are made by rotating the adjustment screw of rear stop positioner 388. This is position P2.
9. The computer is instructed to apply air pressure to move table 184 forward. The view on video screen 310 is inspected and any fine adjustments to the position of the borescope are made by rotating the adjustment screw of forward stop positioner 390. This is position P1.
10. Cursors 316 and 318 are then aligned with the selected points on object image 314 using the user interface provided by computer 228.
11. When each cursor is aligned correctly, computer 228 is commanded to store the cursor positions. The cursors can be aligned and the positions stored either sequentially, or simultaneously, at the option of the user.
12. Computer 228 automatically commands a position reading from position measurement block 470. Computer 228 records this position reading as the position of P1.
13. Computer 228 is instructed to apply air pressure to cylinder 412 to move table 184 rearward. Steps 10 to 12 are repeated for P2.
14. The user commands the computer to calculate and display the true three-dimensional distance between the points selected by the cursors in steps 10 and 13. If desired, the computer can be commanded to also display the absolute positions of each of the two points in the coordinate system that was defined in the operation of the first embodiment.

The mode 2 measurement has a detailed procedure which is modified in a similar manner as compared to the detailed procedure given for the first embodiment.

In this second embodiment, the data acquired and the processing of that data are identical to that described for the first embodiment. If motion errors are to be corrected, the data processing is slightly more involved, and will be discussed below in the section entitled "Operation of Embodiments Using Arbitrary Camera Motion".

F. Description of a Third Embodiment

The mechanical portion of a third embodiment of my invention is shown in an overall perspective view in Figure 20 and in detailed views in Figures 21 through 27. This embodiment implements a new type of rigid

borescope which I call an *electronic measurement borescope* (EMB). Figure 28 is an electronic functional block diagram of the EMB system.

In Figure 20 electronic measurement borescope 500 has a borescope probe tube 512 which itself contains an elongated viewing port 518 at the distal end. At the proximal end of probe tube 512 is located a fiber optic connector 128. Tube 512 is attached to a proximal housing 510, to which is mounted an electronic connector 502. An electronic cable (not shown) connects EMB 500 to a system controller 450 as shown in Figure 28.

Figures 21, 22, and 23 are respectively a plan view and left and right side elevation views of the distal end of electronic measurement borescope 500. In these three views borescope probe tube 512 has been sectioned to allow viewing of the internal components.

In Figures 21 through 23 a miniature video camera 224 is shown mounted to a moving table 184 of a translation stage 180. Camera 224 is made up of a solid state imager 220 and an objective lens 121. Prism 123 redirects the field of view of camera 224 to the side so that the angle between the optical axis of the camera and the translation direction is approximately 90 degrees, or some other substantially side-looking angle as required for the desired application. Solid state imager 220 transmits and receives signals through imager cable 222.

In these figures, the hardware that mounts the lens and the prism has been omitted for clarity. In addition, schematic optical rays are shown in Figures 21 and 22 purely as an aid to understanding. The optical system shown for camera 224 is chosen for illustration purposes, and is not meant to represent the optics that would actually be used in electronic borescope 500. Such optical systems are well known in the art, and are not part of this invention.

Fixed base 182 of translation stage 180 is fastened to distal baseplate 514 which in turn is fastened to borescope probe tube 512.

The position of moving table 184 is controlled by a positioning cable 482, which is wrapped around a positioning pulley 484. Positioning cable 482 is clamped to moving table 184 through a distal motion clamp 486. Pulley 484 is mounted to baseplate 514 through a pulley mounting shaft 485.

Motion clamp 486 supports a distal fiber clamp 492, which in turn supports an illumination fiber bundle 127. Fiber bundle 127 is also supported and attached to moving table 184 by a fiber end clamp 494. Fiber end clamp 494 has internal provision for expanding the bundle of fibers at the end to form fiber output surface 129 (shown in Figure 23).

Fiber bundle 127 and imager cable 222 are both supported by two distal cable stabilizer clamps 490, which are in turn clamped to and supported by positioning cable 482. The more distal cable stabilizer clamp 490 is captured inside a distal stabilizer slot 491, which is itself attached to baseplate 514.

Also mounted to distal baseplate 514 is a transducer mounting bracket 367, which in turn supports a linear position transducer 360. Transducer 360 is attached to moving table 184 through a transducer operating rod 361 and a transducer attachment bracket 369. Position transducer cable 366 extends from the rear of the transducer towards the proximal end of the borescope. Transducer cable 366 is clamped in transducer cable clamp 371 so that tension on cable 366 is not transferred to transducer 360. Clamp 371 is mounted to baseplate 514.

Figures 24 through 27 are respectively a plan view, a left side elevation view, a right side elevation view and a proximal end elevation view of the proximal end of electronic measurement borescope 500. In these views

proximal housing 510 has been sectioned to allow viewing of the internal components.. In Figure 24, borescope probe tube 512 has been sectioned as well, for the same reason.

In Figure 24, imager cable 222, transducer cable 366, and actuator cable 411 have been shown cut short for clarity. In Figure 27, the same cables have been eliminated, for the same reason

In Figures 24 through 27 the proximal end of positioning cable 482 is wrapped around a positioning pulley 484. Pulley 484 is supported by a mounting shaft 485, which in turn is mounted to proximal baseplate 516 through a pulley support bracket 487.

The proximal end of fiber bundle 127 is attached to illumination fiber optic connector 128. The proximal ends of imager cable 222 and position transducer cable 366 are attached to electronic connector 502. Connector 502 is supported by proximal housing 510. Housing 510 also supports borescope probe tube 512 through bulkhead 498. Cables 222 and 366 are clamped in bulkhead 498. Cable 366 is stretched taught between the distal and proximal ends of probe tube 512 before being clamped at both ends, while cable 222 is left slack as shown.

Clamped to positioning cable 482 is a proximal motion clamp 488. Clamp 488 is supported by a proximal translation stage 496, which is in turn mounted to proximal baseplate 516 through a proximal stage support bracket 499.

The position of proximal translation stage 496 is controlled by the action of actuator 410 through actuator attachment bracket 424. Bracket 424 is attached to the moving table of translation stage 496. Actuator 410 contains an actuator output shaft 413 which operates bracket 424 through an actuator attachment bushing 426. Actuator 410 is attached to proximal baseplate 516 through an actuator mounting bracket 422.

Actuator 410 is shown as a motorized micrometer. Actuator electrical cable 411 connects actuator 410 to electronic connector 502.

As shown in Figure 28, electronically this embodiment is very similar to the second embodiment (compare Figure 14). The primary difference is that the video camera back 134 in Figure 14 has been split into solid state imager 220 and imager controller 221 in Figure 28.

G. Operation of the Third Embodiment

This third embodiment contains the essentially the same elements as did the second embodiment, and from the user's standpoint the operation is virtually the same except that now all operations are performed through the user interface of computer 228, and the user makes no mechanical adjustments at all, except for the initial positioning of EMB 500 with respect to the object to be inspected.

The key to this third embodiment is that the motion of actuator 410 is transferred to proximal translation stage 496, thence to positioning cable 482, and finally to moving table 184 at the distal end of the scope. As a result, camera 224 is moved a known distance along a straight line path, which allows one to make dimensional measurements as I have described in the first embodiment. This third embodiment has the advantage that the image quality does not depend on the length of the borescope, thus making this of most interest when the object to be inspected is a long distance from the inspection port.

The optical quality of objective lens 121 can be made higher than the optical quality of a rigid borescope. However, solid state imager 220 will in general not have as high a resolution as do external video imagers such as

video camera back 134 which was used in the first two (BPA) embodiments. Thus the tradeoffs in image quality between the BPA embodiments and this EMB cannot be encompassed by a simple statement.

Distal translation stage 180 is shown implemented in Figures 21 to 23 with a ball bearing slide. This could also be either a crossed roller slide or a dovetail slide. The slide selected will depend on the characteristics of the application of the EMB.

A dovetail slide can be made smaller than either of the other two options, so that the smallest EMB can be made if one were used. A dovetail slide would also have more friction than the other two options, and this would not always be a disadvantage. For instance, if the EMB were to be used in a high vibration environment, the extra friction of a dovetail slide would be valuable in damping oscillations of the translation stage position.

With this third embodiment, any error due to rotational motion of the translation stage will not act through a long lever arm, unlike with the first two (BPA) embodiments. Thus, the translation accuracy of the stage is less critical in this embodiment, which means that it is more feasible to use a less accurate ball or dovetail slide instead of a crossed roller slide.

The elimination of the long lever arm is a second reason why this third embodiment will be preferred when the object to be inspected is distant from the inspection port.

Because fiber bundle 127 is moved along with camera 224, the illumination of the camera's field of view does not change as the camera's position is changed. Both fiber bundle 127 and imager cable 222 must move with the camera, thus they are directly supported by positioning cable 482 to avoid putting unnecessary forces on moving table 184.

It is possible to provide a second pulley and cable arrangement to take up the load of the fiber bundle 127 and imager cable 222, thus eliminating any stretching of positioning cable 482 due to that load, but that makes it more difficult to keep the assembly small, and there is little or no advantage when the position transducer is located at the distal end of the scope, as I have shown.

Distal cable stabilizer clamps 490 fasten fiber bundle 127 and imager cable 222 to positioning cable 482 to keep them out of the way of other portions of the system. Distal stabilizer slot 491 controls the orientation of the more distal stabilizer clamp 490 to ensure that fiber bundle 127 and cables 222 and 482 keep the desired relative positions near stage 180 under all conditions.

Fiber bundle 127 and imager cable 222 must have sufficient length to accommodate the required translation of camera 224. Position transducer cable 366 is of fixed length. Thus, transducer cable 366 is fixed at the proximal end of borescope 500 to bulkhead 498 and is clamped between bulkhead 498 and transducer cable clamp 371 with sufficient tension that it will remain suspended over the length of probe tube 512. Fiber bundle 127 and imager cable 222 are run over the top of transducer cable 366 so that transducer cable 366 acts to prevent fiber bundle 127 and imager cable 222 from contact with positioning cable 482. In this manner, unnecessary increases in the frictional load on positioning cable 482 due to contact with the other cables are avoided.

This simple scheme for keeping the cables apart will work only for a short EMB. For a longer EMB, one can place a second cable spacer and clamp similar to bulkhead 498 near the distal end of probe tube 512, but far enough behind the hardware shown in Figures 21 - 23 so that the cables can come together as shown there. Then all of the cables will be under tension between the proximal and distal ends of the EMB. In such a system, one

could also use a long separating member, placed between positioning cable 482 and the other cables, to ensure that they do not come into contact.

For very long EMBs, it will be necessary to support all of the cables 127, 222, 366, and 482 at several positions along the length of probe tube 512, in order to prevent them from sagging into each other and to prevent positioning cable 482 from sagging into the wall of tube 512. Such support can be provided by using multiple cable spacers fixed at appropriate intervals along the inside of tube 512. These spacers must remain aligned in the correct angular orientation, so that the friction of cable 482 is minimized.

The end of fiber bundle 127 is expanded as necessary in fiber end clamp 494 so that the illumination will adequately cover the field of view of camera 224 at all measurement distances of interest. A lens could be used here as well to expand the illumination beam.

Viewport 518 is large enough to ensure that the field of view of camera 224 is unobstructed for all camera positions available with stage 180. Clearly, this viewport can be sealed with a window (not shown), if necessary, to keep the interior of the distal end of the EMB clean in dirty environments. The window could be either in the form of a flat, parallel plate or in the form of a cylindrical shell, with the axis of the cylinder oriented parallel to the direction of motion of moving table 184. In either case, the tolerances on the accuracy of the geometrical form and position of the window must be evaluated in terms of the effects of those errors on the measurement.

All camera lines of sight will be refracted by the window. This can cause three types of problems. First, the window could cause an increase in the optical aberrations of the camera, which will make the image of the object less distinct. In general this will be a problem only if a cylindrical window is placed with its axis far away from the optical axis of camera 224, or if the axes of the inner and outer cylindrical surfaces of the window are not coincident. Secondly, differences in how the line of sight is refracted over the field of view of the camera will change the distortion of the camera from what it would be without the window in place. This would cause a problem only if the distortion were not calibrated with the window in place. Third, differences in how the line of sight is refracted as the camera is moved to different positions would cause errors in the determination of the apparent positions of a point of interest. This is potentially the largest problem, but once again, it is easily handled by either fabricating and positioning the window to appropriate accuracies, or by a full calibration of the system with the window in place, using the calibration methods to be described later.

It is a design decision whether to locate position transducer 360 at the distal end of EMB 500, as I have shown, or whether to locate it at the proximal end of the scope. Either way will work as long as appropriate attention is paid to minimizing errors. For the distally mounted transducer, because of the small size required, it is not possible to achieve the level of accuracy in the transducer that one can get with the proximally mounted transducer shown in the second embodiment. However, if a proximally mounted transducer is used, one must carefully consider the errors in the transfer of the motion from the proximal to the distal end of the scope.

When it is mounted distally, transducer 360 must be small enough to fit in the space available and have sufficient precision for the purposes of the measurement. Suitable transducers include linear potentiometers or linear variable differential transformers (LVDTs). Note that both of these options are absolute position transducers, so that the issue of determining a home position does not exist if they are used.

Suitable linear potentiometers are available from Duncan Electronics of Tustin, California in the USA or Sfernice of Nice, France. Suitable LVDTs are available from Lucas Control System Products of Hampton, Virginia

in the USA. For instance, model 249 XS-B from Lucas is 4.75 mm diameter by 48 mm long for a measurement range of at least 13 mm.

These small, distally mounted transducers must be calibrated. In fact, LVDT manufacturers provide calibration fixtures, using micrometers as standards. What matters most to the performance of the measurement instrument is repeatability. The repeatability of small linear potentiometers is generally 1 part in 10^4, or 0.0001 centimeter per centimeter of travel. The repeatability of an LVDT is determined by the signal to noise ratio of the signal processing electronics. A signal to noise ratio of 1 part in 10^5 is easily obtained with small signal bandwidth, and 1 part in 10^6 is quite feasible, though more expensive to obtain. These available levels of repeatability are quite consistent with the purposes intended for the instrument.

If the EMB is to be used over a large range of temperatures, it will be necessary to include a temperature transducer at the distal end of the scope, so that the temperature sensitive scale factor of the distal position transducer can be determined and taken into account in the measurement.

With the distally mounted position transducer, the only backlash that matters is the backlash between moving table 184 and position transducer 360 due to the necessary clearance between transducer operating rod 361 and transducer attachment bracket 369. This backlash will not be negligible, in general, so that the measurement procedure must use the anti-backlash elements of the measurement procedure detailed above in the description of the first embodiment. (Briefly, this means that the camera position is always determined with the camera having just moved in one particular direction.) Since the system shown in Figure 28 is a closed - loop positioning system, it is straightforward to implement anti-backlash procedures automatically in the positioning software, and the user then need not be concerned with them.

The position transducer will not correctly measure the position of the camera if the measurement axis of the transducer is misaligned with the axis of camera motion. Such a misalignment causes a so-called "cosine" error, because the error is proportional to the cosine of the angular misalignment. This error is small for reasonable machining and assembly tolerances. For instance, if the misalignment is 10 milliradians (0.6 degrees), the error in the distance moved between camera positions is 1 part in 10^4. When necessary for very accurate work, this error can be determined and taken into account in the measurement, by scaling the transducer position data accordingly. The first two embodiments are also subject to this error, but in those cases the necessary mechanical tolerances are easier to achieve. Note that an instrument suffering from this error will systematically determine distances to be larger than they really are.

There could be a thermal drift of the camera position if positioning cable 482 has different temperature coefficient of expansion than does probe tube 512 or if the instrument is subjected to a temperature gradient. Such a drift would not be a problem over the small time that it takes to make a measurement, because it is only the differential motion of the camera between viewing positions P1 and P2 that is important. In more general terms, it doesn't matter if there is a small variable offset between proximal position commanded and the distal position achieved, as long as any such offset is constant over a measurement. As previously discussed, a large offset could be a problem if one desires to correct for errors in the motion of translation stage 180.

Of course, differential thermal expansion of positioning cable 482 and borescope tube 512 would cause a varying tension in cable 482. Thus, unless cable 482 and 512 are made of materials with the same expansion coefficient, it may be necessary to spring load pulley support bracket 487. Whether such spring loading is

necessary is dependent on the length of tube 512 and the temperature range over which the EMB must operate, as well as the difference in temperature coefficients.

A significant level of static friction (stiction) in translation stage 180 would require that the EMB be implemented with a distal position transducer, since otherwise there would be considerable uncertainty added to the position of the camera. Dovetail slides tend to have significant stiction, so that use of a dovetail slide will almost certainly require a distal position transducer. If the stiction is too severe, the position setability of the camera will be compromised, which could make the instrument frustrating to use.

Clearly, the EMB could be implemented with another sort of motion actuator 410, for instance, an air cylinder. I have shown that there is used a proximal translation stage 496 between actuator 410 and positioning cable 482. Clearly, this is not strictly necessary as cable 482 could be clamped directly to output shaft 413 of actuator 410, provided that output shaft 413 does not rotate and can sustain a small torque.

The EMB could also be implemented with a miniature motor and lead screw placed at distal end. This eliminates the requirement for transfer of motion from the proximal to the distal end, but it then requires more space at the distal end. The advantage is that this could be used to embody an electronic measurement endoscope, that is, a flexible measurement scope. Such a scope would be flexible, except for a relatively short rigid part at the distal end.

H. Description of a Fourth Embodiment

Figures 29 and 30 show respectively plan and left side elevation views of the distal end of a fourth mechanical embodiment of the invention, which I call the *electronic measurement endoscope* (EME). This fourth embodiment is similar to the third embodiment, except that the positioning pulley and cable system has been replaced here by a positioning wire 532 which is enclosed except at its distal and proximal ends by a positioning wire sheath 534.

In Figures 29 and 30 many of the same elements are shown as in the third embodiment, and only those elements most directly related to the discussion of this fourth embodiment are identified again.

The distal end of positioning wire 532 is clamped by distal positioning wire clamp 542. Clamp 542 is attached to the moving table of translation stage 180. Positioning wire sheath 534 is clamped to distal baseplate 514 with a distal sheath clamp 536.

The external housing of the endoscope now consists of two portions, a flexible endoscope envelope 538 and a distal rigid housing 540. Rigid housing 540 is attached to the end of flexible envelope 538 to form an endoscope which is flexible along most of its length, with a relatively short rigid section at its distal end.

Flexible envelope 538 includes the necessary hardware to allow the end of the endoscope to be steered to and held at a desired position under user control. Such constructions are well known in the art and are not part of this invention.

As in the third embodiment, imager cable 222 and illumination fiber bundle 127 are supported by and clamped to the element which transfers motion from the proximal to the distal end of the scope. Here cable 222 and fiber bundle 127 are clamped by a distal cable stabilizer clamp 490 which is itself clamped to positioning wire 532. *Also as in* the third embodiment, clamp 490 is captured inside distal stabilizer slot 491 to control its position and orientation.

As in the third embodiment, the distal end of illumination fiber bundle 127 is supported by distal fiber clamp 492 and fiber end clamp 494. In this embodiment, fiber clamp 492 is attached to positioning wire clamp 542.

Imager cable 222, illumination fiber bundle 127, position transducer cable 366, and positioning wire sheath 534 all pass through and are clamped to distal end cable clamp 544, which is located at the proximal end of distal rigid housing 540. Positioning wire sheath 534 is positioned in the center of cable clamp 544, while the other three cables are arranged around it in close proximity. Positioned at suitable intervals within flexible endoscope envelope 538 are a number of cable centering members 546, through which all of the cables pass.

The position of stage 180 is monitored by linear position transducer 360, which is mounted to distal baseplate 514 with transducer mounting bracket 367.

I. Operation of the Fourth Embodiment

Clearly, if the proximal end of sheath 534 is clamped to proximal baseplate 516 of the third embodiment, and if actuator 410 is attached to positioning wire 532, then the motion of the actuator will be transferred to distal translation stage 180. Thus, the operation is identical to that of the third embodiment, except that this embodiment is now a flexible measurement endoscope which can be brought into position for measurements in a wider range of situations.

When this EME is steered to a desired position, flexible envelope 538 will necessarily be bent into a curve at one or more places along its length. Bending envelope 538 means that one side of the curve must attain a shorter length, and the opposite side a longer length, than the original length of the envelope. The same holds true for components internal to envelope 538, if these components have significant length and are not centered in envelope 538. Thus, in order to prevent the bending of the EME from affecting the position of translation stage 180, it is necessary to ensure that positioning wire 532 runs down the center of envelope 538. Cables 222, 366, and fiber bundle 127 are also run as close to the center of envelope 538 as feasible, to minimize the stress on these cables as the EME is steered.

This embodiment almost certainly requires the use of a distally located linear position transducer 360, as shown, because there is likely to be considerable stiction in the motion of positioning wire 532 inside sheath 534.

Imager cable 222 and illumination fiber bundle 127 must have sufficient length to reach the most distal position of stage 180. These, as well as cable 366, are clamped to housing 540 through distal end cable clamp 544 so that no forces can be transferred from them to the measurement hardware inside housing 540. As the EME is bent, there will be small changes in the lengths of cables 222 and 366 and fiber bundle 127. Thus, there must be sufficient extra length of these cables stored at the proximal end, or throughout the length of the endoscope, so that no large forces are generated when the EME is bent.

When stage 180 is moved away from its most distal position, the portion of cable 222 and fiber bundle 127 which are contained within housing 540 will bend so as to store their now excess lengths in the portion of housing 540 behind the proximal end of baseplate 514.

J. Embodiments Using Other Camera Motions

1. Introduction

In the preferred embodiments, I teach the use of straight line camera motion between viewing positions, with a fixed camera orientation, to perform the perspective measurement. The reasons that I prefer these embodiments are that they are simple and of obvious usefulness. However, my system is not restricted to the use of straight line camera motion or fixed camera orientation. Other camera motions are possible and can also be used when making a perspective measurement. Some of these more general camera motions will be useful for specific applications. Below, I show how to perform the measurement when using any arbitrary motion of the camera, and when using multiple cameras.

This generalized method of perspective dimensional measurement that I teach here has an important application in improving the accuracy of the measurement made with my preferred embodiments. Even with the best available hardware, the motion of the camera will not conform to a perfect straight line translation. In this section, I show how to take such motion errors into account when they are known. In the calibration section I will show how to determine those errors.

2. Linear Camera Motion

Figure 31 depicts the geometry of a mode 2 perspective measurement of the distance between the points A and B being made with a camera moving along a linear path, but where the camera orientation does not remain constant as the camera position changes. Compare Figure 31 to Figure 13. In Figure 31, the points A and B are chosen to lie at considerably different distances (ranges) from the path of the camera in order to emphasize the differences that a variable camera orientation creates.

The situation shown in Figure 31 represents the geometry of a measurement which may be made with any number of different physical systems. For instance, the camera could be movable to any position along the path, and the camera could be rotatable to any orientation with respect to that path. Or, the camera rotation could be restricted, for instance, to be about an axis perpendicular to Figure 31. Another possibility is that the camera orientation is restricted to only a relatively small number of specific values, such as, for instance, the two specific orientations shown in the Figure. A third possibility is that the positions the camera can take are restricted to a relatively small number, either in combination with rotational freedom or in combination with restricted rotation.

If either the positions or the orientations of the camera are small in number, then one can use the well-known kinematic mounting principle to ensure that these positions and/or orientations are repeatable to a high degree of accuracy.

The basic concept of the measurement geometry shown in Figure 31 is that the camera is rotated towards the point of interest at any viewing position. This is useful, for instance, when the camera has a narrow field of view, and when one desires to use a long perspective baseline. One wants to use a long perspective baseline because it minimizes the random error in the measurement. In fact, one can show that for optimum measurement results, one wants to set the baseline at a value that keeps the angle subtended at each point of interest by the two viewing positions approximately constant for points at various ranges from the instrument. This is just the situation shown in Figure 31, where the angles formed by the dot-dash lines are the same for both point A and point B.

The disadvantage of the measurement geometry shown in Figure 31 is that it requires accurately known camera motion in two degrees of freedom rather than just one, as do my preferred embodiments. Its advantage is that it provides the smallest possible random measurement error.

It should also be clear to the reader that two cameras could be used to make the measurement depicted in Figure 31. If two cameras are used, it is still necessary to move one of the cameras with respect to the other to adjust the perspective baseline to the optimum value, when locating points at different ranges and relative positions. When viewing an inaccessible object, the preferred implementation is to mount both cameras to a single probe assembly, but it is also possible to mount each camera on a separate probe, just as long as the relative positions and orientations of the cameras are known accurately. I discuss below the parameters of the measurement geometry which must be known in order to make the measurement in the most general case.

One advantage of a two camera system is that the requirement for a second degree of freedom of motion can be eliminated under certain conditions, since the orientation of each of the cameras could be fixed at a suitable angle for the measurement, and the point of interest could then be brought into the field of view of each camera by translating the camera to an appropriate point along the path. This situation can be envisioned from Figure 31 by assuming that there is an upper camera, which is used at the viewing positions P2A and P2B, and a lower camera, which is used at the viewing positions P1A and P1B, and that both cameras can be moved along the single line of motion shown in the Figure.

A second advantage of a two camera system is that the measurement data can be acquired in the time necessary to scan one video frame, once the cameras are in position, if the digital video "frame grabber" technology mentioned earlier is used. Such quasi-instantaneous measurements are useful if the object is moving or vibrating. For the same reason, such a system could reduce the stability requirements on the mounting or support structure for the measurement instrument.

A disadvantage of a two camera implementation of the measurement shown in Figure 31 is that there will be a minimum perspective baseline set by the physical size of the cameras. If the camera orientations are fixed, the minimum perspective baseline implies a minimum measurement range. A second disadvantage of the fixed camera orientation variant of the two camera system is that there is also a maximum measurement range for camera fields of view smaller than a certain value, since there will always be a maximum value of the perspective baseline.

3. Circular Camera Motion

Figure 32 depicts a mode 1 perspective measurement being made with a camera moving along a curved path. The curve is a section of a circular arc, with a radius of curvature R_p and center of curvature at C. The optical axis of the camera lies in the plane containing the circular path. The camera orientation is coupled to its translation along the path so that the optical axis of the camera always passes through C as the camera moves along the path.

The advantage of this arrangement, as compared to my preferred embodiments, is that a much larger perspective baseline can be used without losing the point of interest from the camera field of view, for objects located near the center of curvature, C, when the field of view of the camera is narrow. Thus, the measurement system shown in Figure 32 can potentially provide lower random measurement errors.

As is clear from Figure 32, there will usually be a maximum range for which perspective measurements can be made, as well as a minimum range, at any given value of the perspective baseline. In order to make measurements at large ranges, the system of Figure 32 requires a smaller baseline to be used than does a similar straight line motion system. For certain combinations of d, R_p, and camera field of view it is possible for both the minimum and maximum measurement ranges to decrease as d increases. Thus, this curved camera path system has the disadvantage, as compared to my preferred embodiments, of having a limited span of ranges over which measurements can be made.

This curved camera path system would be preferred in cases where only a small span of object ranges are of interest, and where there is plenty of space around the object to allow for the relatively large camera motions which are feasible. I consider the primary operating span of ranges of the circular camera path system shown in Figure 32 to be $(0 \leq z \leq 2R_p)$.

Another disadvantage of the system shown in Figure 32 for the measurement of inaccessible objects is the difficulty of moving the required hardware into position through a small inspection port.

The method chosen for using a transducer to determine the camera's position along the path will depend on how this path is generated mechanically. For instance, if a circular path is generated by swinging the camera about a center point, then the position will probably be most conveniently transduced as an angular measurement. If the path is generated by moving the camera along a circular track, then the position will probably be transduced as a linear position. The method of transducing the position of the camera becomes an issue when considering how to describe an arbitrary motion of the camera, as I discuss below.

Two cameras can be used with the circular camera path just as in the case of a linear camera path. In fact, mode 2 measurements can use up to four cameras to make the measurement, with either linear or circular camera motion. Multiple cameras can be used with any camera path, and in fact, there is no need for all cameras to follow the same path. The fundamental requirements, as will be shown, are simply that the relative positions and orientations as well as the distortions and effective focal lengths of all cameras be known.

A system using another potentially useful camera motion path is shown in Figure 33. Here the camera is moved in a circular arc, as in Figure 32, but now the camera is oriented to view substantially perpendicular to the plane of the arc. In Figure 33 a tiny video camera is placed at the tip of a rigid borescope, similar to my third and fourth preferred embodiments. This borescope has an end section with the capability of being erected to a position perpendicular to the main borescope tube. When this erection is accomplished the camera looks substantially along the axis of the borescope. To make the perspective measurement, the borescope (or some distal portion of it) is rotated about its axis, thus swinging the camera in a circular path. In this case it is the rotation of the camera about the optical axis which is coupled to the translation of the camera. The camera position would be transduced by an angular measurement in this system.

An advantage of the system shown in Figure 33 is that it allows both large and small perspective baselines to be generated with an instrument that can be inserted through a small diameter inspection port. Of course, it still would require that there be considerable space in the vicinity of the objects to be inspected to allow for the large motions which can be generated.

The instrument shown in Figure 33 could combine the circular motion just described with an internal linear motion as in my fourth embodiment to offer the capability of making measurements either to the side or in the forward direction.

K. Operation of Embodiments Using Arbitrary Camera Motion

1. Description of Arbitrary Camera Motion

I must first explain how I describe an arbitrary camera motion, before I can explain how to make a measurement using it. To make accurate measurements, the motion of the camera must be accurately known, either by constructing the system very accurately to a specific, known geometry, or by a process of calibration of the motion. If calibration is to used to determine the motion of the camera, then that motion must be repeatable to the required level of precision, and the method of calibration must have the requisite accuracy.

In general, the true position of the camera along its path is described by a scalar parameter p. This parameter could be a distance or an angle, or some other parameter which is convenient for describing the camera position in a particular case.

The position of the camera is monitored by a transducer which produces an output $\eta(p)$. Here, η is an output scalar quantity which is related to the true position along the path, p, by a calibration curve $p(\eta)$.

The geometrical path of the camera in space is expressed as a vector in some convenient coordinate system. That is, the physical position of the camera (more precisely, the position of the nodal point of the camera's optical system) in space is expressed as a vector, $\mathbf{r}_c(p(\eta))$ or $\mathbf{r}_c(\eta)$, in a coordinate system that I call the *external* coordinate system or the *global* coordinate system.

Likewise, the orientation of the camera in space is expressed a rotation matrix, which describes the orientation of the camera's internal coordinate system with respect to the global coordinate system. Thus, the camera's orientation at any point along its path is expressed as $\mathbf{R}_c(p(\eta))$ or $\mathbf{R}_c(\eta)$. The matrix $\mathbf{R}_c$ transforms any vector expressed in the global coordinate system into that vector expressed in the camera's internal coordinate system. The matrix $\mathbf{R}_c$ is the product of three individual rotation matrices, each of which represents the effect of rotation of the camera's coordinate system about a single axis:

$$\mathbf{R}_c(\eta) = \mathbf{R}_z(\theta_z(\eta))\, \mathbf{R}_y(\theta_y(\eta))\, \mathbf{R}_x(\theta_x(\eta)) \tag{31}$$

where θ_z, θ_y, and θ_x are the angles that the coordinate system has been rotated about the corresponding axes.

Now, in general, the terms $\mathbf{r}_c(\eta)$ and $\mathbf{R}_c(\eta)$ will not be independent quantities, but will be coupled together by the geometry and construction of the perspective measurement system. An example was shown in Figure 32, where the camera's orientation is coupled to its position, so that the optical axis always passes through the center of curvature of the camera's path.

If two or more cameras are used, then each one will have a location and orientation expressed similarly. I will assume that the same global coordinate system is used to describe the motion of all cameras. This must be the case, but if at some point in the process separate global coordinate systems are used, and if the relationships between these separate global coordinate systems are known, then it is possible to express all of the camera motions in a single global coordinate system in the manner shown below for expressing one coordinate system in terms of another.

To summarize the relationship between camera motion and the measurement, what is required is that the positions and orientations of the camera(s) be accurately known relative to an external (global) coordinate system. This coordinate system is fixed with respect to the instrument apparatus, but it has no inherent relationship to the object being measured. The position of the object in the global coordinate system becomes fixed only when the instrument is itself fixed at some convenient position with respect to the object. When this is done, the position of points on the object can be determined in the global coordinate system, or in some other closely related coordinate system which is also fixed with respect to the instrument apparatus.

2. The General Perspective Measurement Process

Above, I taught how to perform the perspective measurement when the camera undergoes a pure translation. Now consider the case where the camera undergoes a rotation as well as a translation between viewing positions P1 and P2.

Considering again Figure 12, an arbitrary vector $\mathbf{r}_1$ can be expressed as:

$$\mathbf{r}_1 = \mathbf{d} + \mathbf{r}_2 \tag{32}$$

where the vector $\mathbf{r}_2$ is drawn from the origin of the P2 coordinate system to the end of vector $\mathbf{r}_1$. Any or all of these vectors could be expressed in either coordinate system. I choose to define them as being expressed in P1 coordinates. Then $\mathbf{r}_2 = \mathbf{r}_1 - \mathbf{d}$ can be re-expressed in the P2 coordinate system by using the transformation that the coordinates of a point undergo when a coordinate system is rotated about its origin.

It is a fact that there is no single set of coordinates that can be defined that will uniquely represent the general rotation of an object in three dimensional space. That is, for any coordinate system one might choose, the order in which various sub-rotations are applied will affect the final orientation of the object. Thus, one must make a specific choice of elemental rotations, and the order in which they are applied, to define a general rotation.

The way that coordinate system rotations are most often defined is to begin with the two coordinate systems in alignment. Then one system is rotated about each of its coordinate axes in turn, to produce the final alignment of the rotated coordinate system. I define the procedure for rotating coordinate system P2, beginning with it aligned with P1, to obtain the rotated coordinate system P2 as the following:

1. Rotate P2 about $\hat{x}_2$ by an angle θ_x.
2. Rotate P2 about $\hat{y}_2$ by an angle θ_y.
3. Rotate P2 about $\hat{z}_2$ by an angle θ_z.

This procedure means that the effect of this rotation of the P2 coordinate system with respect to the P1 coordinate system on the coordinates of a point in space can be expressed in the P2 system as the product of a rotation matrix with the vector from the origin to the point. That is:

$$\mathbf{v}_2 = \mathbf{R}\,\mathbf{v}_1 \tag{33}$$

or

$$\mathbf{v}_2 = \mathbf{R}_z(\theta_z)\,\mathbf{R}_y(\theta_y)\,\mathbf{R}_x(\theta_x)\,\mathbf{v}_1 \tag{34}$$

where

$$
\mathbf{R}_z(\theta_z) = \begin{bmatrix} \cos\theta_z & \sin\theta_z & 0 \\ -\sin\theta_z & \cos\theta_z & 0 \\ 0 & 0 & 1 \end{bmatrix} \tag{35}
$$
$$
\mathbf{R}_y(\theta_y) = \begin{bmatrix} \cos\theta_y & 0 & -\sin\theta_y \\ 0 & 1 & 0 \\ \sin\theta_y & 0 & \cos\theta_y \end{bmatrix}
$$
$$
\mathbf{R}_x(\theta_x) = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_x & \sin\theta_x \\ 0 & -\sin\theta_x & \cos\theta_x \end{bmatrix}
$$

and where $\mathbf{v}_1$ is the vector between the origin of the P2 coordinate system and the point as expressed in the unrotated P1 coordinate system and $\mathbf{v}_2$ is the same vector as expressed in the rotated P2 coordinate system.

The transformation to go the other way, that is, to change coordinates as measured in the rotated P2 system to coordinates measured in the P1 system is:

$$
\begin{aligned}
\mathbf{v}_1 &= \mathbf{R}^{-1}\,\mathbf{v}_2 \\
\mathbf{v}_1 &= \mathbf{R}_x^{-1}(\theta_x)\,\mathbf{R}_y^{-1}(\theta_y)\,\mathbf{R}_z^{-1}(\theta_z)\,\mathbf{v}_2 \\
\mathbf{v}_1 &= \mathbf{R}_x(-\theta_x)\,\mathbf{R}_y(-\theta_y)\,\mathbf{R}_z(-\theta_z)\,\mathbf{v}_2
\end{aligned} \tag{36}
$$

Consider again the perspective measurement process. At viewing position P1, visual coordinate location measurements are made in a coordinate system which depends on the orientation of the camera at that position. When nodal point of the camera is moved to position $\mathbf{d}_{v1}$ as measured in the P1 coordinate system, the camera will rotate slightly, so that the visual coordinate system at position P2 is not the same as it was at position P1. I refer to the rotation matrix, which transforms coordinates measured in the visual coordinate system at P1 to coordinates measured in the visual coordinate system at P2, as $\mathbf{R}_{12}$. Clearly this rotation matrix is a product of three simple rotations, as detailed in (34) and (35). But, I have shown how to express measurements made in the P2 coordinate system in terms of the P1 coordinate system:

$$
\mathbf{r}_{v1} = \mathbf{R}_{12}^{-1}\,\mathbf{r}_{v2} \tag{37}
$$

so that Equations (12) can now be expressed as:

$$
\begin{aligned}
\mathbf{r}_{v1} &= z_{v1}\mathbf{a}_{v1} \\
\mathbf{r}_{v1} &= \mathbf{R}_{12}^{-1}\,z_{v2}\mathbf{a}_{v2} + \mathbf{d}_{v1}
\end{aligned} \tag{38}
$$

and these can be solved as above to get:

$$
\mathbf{r}_{v1} = \frac{1}{2}\Big[[\,\mathbf{a}_{v1} \quad \mathbf{R}_{12}^{-1}\,\mathbf{a}_{v2}\,][\,\mathbf{a}_{v1} \quad -\mathbf{R}_{12}^{-1}\,\mathbf{a}_{v2}\,]^{LI} + \mathbf{I}_3\Big]\mathbf{d}_{v1} \tag{39}
$$

where, to repeat, $\mathbf{d}_{v1}$ is the translation of the camera nodal point between positions P1 and P2 as expressed in the P1 coordinate system.

In analogy with (18) and (19) I define a new coordinate system:

$$
\mathbf{r}_m = \mathbf{r}_{v1} - \frac{1}{2}\,\mathbf{d}_{v1} \tag{40}
$$

Then:

$$
\mathbf{r}_m = \frac{1}{2}[\,\mathbf{a}_{v1} \quad \mathbf{R}_{12}^{-1}\,\mathbf{a}_{v2}\,][\,\mathbf{a}_{v1} \quad -\mathbf{R}_{12}^{-1}\,\mathbf{a}_{v2}\,]^{LI}\,\mathbf{d}_{v1} \tag{41}
$$

Comparing (41) to (19) shows that any camera rotation between viewing positions P1 and P2 is easily taken into account in the perspective measurement, as long as that rotation is known.

In measurement mode 1, the experimental data obtained are four camera image position coordinates $(x'_{im1}, y'_{im1}, x'_{im2}, y'_{im2})$ for each object point of interest and the readings of the camera position transducer, η_1 and η_2, at the two viewing positions P1 and P2.

As explained for the first preferred embodiment, the data processing begins by correcting the measured image point location data for distortion as expressed by Equation (22). Next, the data are scaled by the inverse of the effective focal length of the combined optical-video system as expressed by Equation (23). Then, for each object point of interest, the visual location vectors $\mathbf{a}_{v1}$ and $\mathbf{a}_{v2}$ are formed as expressed in Equation (24).

Next, the displacement vector between the two viewing positions is calculated in global coordinates as:

$$\mathbf{d}_g(\eta_2,\eta_1) = \mathbf{r}_c(\eta_2) - \mathbf{r}_c(\eta_1) \tag{42}$$

As stated previously, I call this vector the *perspective displacement*.

The relative rotation of the camera between the two viewing positions is calculated as:

$$\mathbf{R}_{12}(\eta_2,\eta_1) = \mathbf{R}_c(\eta_2)\,\mathbf{R}_c^{-1}(\eta_1) \tag{43}$$

Equation (43) simply says that the rotation of the camera between positions P1 and P2 is equivalent to the rotation of the camera in global coordinates at P2 minus the rotation it had at P1.

The perspective displacement is re-expressed in the camera internal coordinate system at P1 by taking into account the rotation of the camera at that point. That is:

$$\mathbf{d}_{v1} = \mathbf{R}_c(\eta_1)\,\mathbf{d}_g(\eta_2,\eta_1) \tag{44}$$

The location of the object point of interest in the measurement coordinate system is then computed as:

$$\mathbf{r}_m = \frac{1}{2}[\mathbf{a}_{v1} \quad \mathbf{R}_{12}^{-1}\,\mathbf{a}_{v2}][\mathbf{a}_{v1} \quad -\mathbf{R}_{12}^{-1}\,\mathbf{a}_{v2}]^{LI}\,\mathbf{d}_{v1} \tag{45}$$

where the measurement coordinate system is parallel to the internal coordinate system of the camera at P1, with its origin located midway between P1 and P2.

Equation (45) expresses how to locate a point in the measurement coordinate system under completely general conditions, for any arbitrary motion of the camera, provided that the motion is known accurately in some global coordinate system. If the motion is repeatable, it can be calibrated, and thus known. Equation (45) is the fully three-dimensional least squares estimate for the location of the point.

To complete the mode 1 perspective dimensional measurement process, Equation (45) is used for both points A and B individually, then Equation (7) is used to calculate the distance between these points.

It is important to note that if multiple image position coordinate measurements are made for the same object points under exactly the same conditions in an attempt to lower the random error, then one should average the individual point location measurements given by Equation (45) <u>before</u> calculating the distance between the points using Equation (7). This gives a statistically unbiased estimate of the distance. If one instead calculates a distance estimate with each set of measurements and then averages them, one obtains what is known as an asymptotically biased estimate of the distance.

If two cameras are used, one simply uses each individual camera's distortion parameters to correct the image measured with that camera as in Equation (22). Then, the scaling by the inverse focal length is carried out for each individual camera as expressed by Equation (23). Then, for each object point of interest, the visual location vectors $\mathbf{a}_{v1}$ and $\mathbf{a}_{v2}$ are formed as expressed in Equation (24), where now the data in $\mathbf{a}_{v1}$ were determined with one of the cameras and the data in $\mathbf{a}_{v2}$ were determined with the other. The remainder of the data processing is identical whether one or two cameras are used to make the measurement.

The geometry of measurement mode 2 for an arbitrary camera motion is depicted in Figure 34. The experimental data obtained are four camera image position coordinates $(x'_{im1}, y'_{im1}, x'_{im2}, y'_{im2})$ and the two readings of the camera position transducer η_1 and η_2, for each object point of interest. In this mode of measurement, the camera positions are not the same for each point of interest, so that there may be either three or four camera positions used for each distance to be determined.

Figure 34 depicts the situation when the distance between two points, A and B, is to be determined. It is clear that this measurement mode makes sense only for a certain class of camera motion, object distance, object shape combinations. For instance, with the camera motion shown in Figure 32, and a more or less planar object located near the center of curvature, C, there is little or no ability to view different portions of the object by moving the camera, so that there is no reason to use measurement mode 2.

However, as shown in Figure 35, there are other situations when only the use of measurement mode 2 makes a measurement feasible. In Figure 35, the distance between two points on opposite sides of an object is desired. The object has a shape and an orientation such that both points cannot be viewed from any single camera position which is physically accessible. As shown in Figure 35, the combination of circular camera motion and measurement mode 2 allows this measurement to be made. This measurement could also be made with an arbitrary camera rotation embodiment of the system shown in Figure 31.

Consider now that the measurements depicted in Figure 34 or 35 are to be performed. Say that the camera position transducer readings are $\{ \eta_{1A}, \eta_{2A}, \eta_{1B}, \eta_{2B} \}$ at viewing positions {P1A, P2A, P1B, P2B} respectively. Then, the actual camera positions in the global coordinate system are $\{ \mathbf{r}_c(\eta_{1A}), \mathbf{r}_c(\eta_{2A}), \mathbf{r}_c(\eta_{1B}), \mathbf{r}_c(\eta_{2B}) \}$ respectively. Likewise, the orientations of the camera's coordinate system with respect to the global coordinate system are $\{ \mathbf{R}_c(\eta_{1A}), \mathbf{R}_c(\eta_{2A}), \mathbf{R}_c(\eta_{1B}), \mathbf{R}_c(\eta_{2B}) \}$.

In measurement mode 2, the positions of the points A and B are each determined independently by the basic point location process expressed by Equation (45) to give $\mathbf{r}_{mA}$ and $\mathbf{r}_{mB}$ respectively. According to that process, $\mathbf{r}_{mA}$ is determined in a measurement coordinate system parallel to the coordinate system of the camera at P1A, while $\mathbf{r}_{mB}$ is determined in a coordinate system which is parallel to the camera coordinate system at P1B.

The location vectors for points A and B are then re-expressed in the global coordinate system as:

$$\begin{aligned} \mathbf{r}_{AG} &= \mathbf{R}_c^{-1}(\eta_{1A})\,\mathbf{r}_{mA} \\ \mathbf{r}_{BG} &= \mathbf{R}_c^{-1}(\eta_{1B})\,\mathbf{r}_{mB} \end{aligned} \tag{46}$$

and the vector between the origin of the A measurement coordinate system and the origin of the B coordinate system in global coordinates is calculated as (Figure 34):

$$\mathbf{d}_{AB} = \frac{1}{2}\left[\mathbf{r}_c(\eta_{1A}) + \mathbf{r}_c(\eta_{2A}) - \mathbf{r}_c(\eta_{1B}) - \mathbf{r}_c(\eta_{2B}) \right] \tag{47}$$

Finally, the distance between points A and B is calculated as:

$$r = |\mathbf{r}| = |\mathbf{d}_{AB} + \mathbf{r}_{AC} - \mathbf{r}_{BG}| \tag{48}$$

Once again, if two or more cameras are used, one need only correct the image locations for distortion and scale the image locations by the inverse focal length for each camera individually to perform the measurement, just as long as the positions and orientations of the cameras are all expressed in the same global coordinate system. And, just as before, if multiple identical measurements are made, one should calculate the average location vectors before calculating the distance with Equation (48), rather than averaging individual distance determinations.

3. Application of the General Process to Correction of Translation Stage Rotational Errors

I have shown four preferred embodiments of my apparatus, where in each case, a single camera will be moved along a substantially straight line. If the motion is a perfect translation, then in Equations (43) and (44), $\mathbf{R}_c(\eta_2)$ is equal to $\mathbf{R}_c(\eta_1)$, $\mathbf{R}_{12}$ is the 3 x 3 identity matrix, and the direction of perspective displacement $\mathbf{d}_g(\eta_2,\eta_1)$, hence $\mathbf{d}_{v1}$, remains the same for any (η_2,η_1). In this case $\mathbf{R}_c$ is identified with the product $\mathbf{R}_z\,\mathbf{R}_y$, which simply makes use of the fact that the orientation of a vector can always be expressed by at most two angles, since a vector is not changed by a rotation about itself. Finally, with a perfect straight line translation of the camera, Equation (45) reduces to Equation (27).

As an example of the use of the general measurement process to correct for errors of motion, consider the third (EMB) and fourth (EME) preferred embodiments. Assume that the translation stage has rotational errors, which have been characterized with a calibration process, which will be described later. As a result of this calibration, the translation stage rotational error $\mathbf{R}(\eta)$ is known in some calibration coordinate system. To simplify the calibration task, I specify that the calibration coordinate system be the same as the global coordinate system, and I explain later how to ensure this. I further specify that the global coordinate system has its x axis along the nominal translation direction, which is simply a matter of definition.

The errors of translation stages are not well specified by their manufacturers. For typical small ball bearing translation stages, a comparison of various manufacturers' specifications is consistent with expected rotational errors of approximately 300 microradians and transverse translational errors of about 3 microns. A moment of thought will convince the reader that with these levels of error, the rotational error will contribute more to the measurement error of the system than will the translation error for any object distance larger than 10 mm. Thus, for measurements of objects which are at distances greater than 10 mm, it is reasonable to correct for only the rotational error of the translation stage. I now show how to do this.

The image point location data are processed in the same manner as has already been described. The position of the camera nodal point can be expressed as:

$$\mathbf{r}_c(\eta) = \begin{bmatrix} p(\eta) \\ 0 \\ 0 \end{bmatrix} = \mathbf{p}(\eta) \tag{49}$$

so that the perspective displacement in global coordinates is calculated as:

$$\mathbf{d}_g(\eta_2,\eta_1) = \mathbf{r}_c(\eta_2) - \mathbf{r}_c(\eta_1) = \mathbf{p}(\eta_2) - \mathbf{p}(\eta_1) \tag{50}$$

For any position of the camera, the rotational orientation of the camera can be expressed as

$$\mathbf{R}_c(\eta) = \mathbf{R}_{cg}\mathbf{R}(\eta) \tag{51}$$

where $\mathbf{R}_{cg}$ is the orientation of the camera with respect to the global coordinate system at some reference position where $\mathbf{R}(\eta)$ is defined to be the identity matrix. Both $\mathbf{R}_{cg}$ and the rotational error, $\mathbf{R}(\eta)$, are determined in the calibration process.

As the next step in measurement processing, then, the relative rotation of the camera between positions P1 and P2 is calculated as:

$$\mathbf{R}_{12}(\eta_2,\eta_1) = \mathbf{R}_c(\eta_2)\,\mathbf{R}_c^{-1}(\eta_1) = \mathbf{R}_{cg}\mathbf{R}(\eta_2)\,\mathbf{R}^{-1}(\eta_1)\mathbf{R}_{cg}^{-1} \tag{52}$$

Since the rotation matrices are orthogonal, their inverses are simply calculated as their transposes.

The perspective displacement is then transformed to the camera coordinate system at P1 as:

$$\mathbf{d}_{v1} = \mathbf{R}_{cg}\mathbf{R}(\eta_1)[\mathbf{p}(\eta_2) - \mathbf{p}(\eta_1)] \tag{53}$$

and finally the position of the point of interest is calculated by using results (52) and (53) in Equation (45), and distances between points of interest are calculated with Equation (7).

Note that the process I have just outlined implicitly includes the possibility of correction of position transducer errors, given by the calibration curve $p(\eta)$.

If transverse translation errors of the stage are to be corrected, then the calibration process must determine these errors, and the correction data must be incorporated into the general measurement formalism given in the previous section in a similar manner to that shown here for rotational errors.

L. Calibration

I find it convenient to divide the calibrations of my measurement system into three classes, which I call optical calibration, alignment calibration, and motion calibration.

In optical calibration, the optical properties of the camera when it is considered simply as an image forming system are determined. In alignment calibration, additional properties of the camera which affect the dimensional measurement are determined. Both of these classes of calibration must be accomplished in order to make a measurement with my technique. Optical calibration has been briefly considered in some of the prior art of endoscopic measurements, while alignment calibration is new.

Motion calibration is not necessarily required to make a measurement, but it may be required in order to make measurements to a specific level of accuracy. Whether this calibration is required or not is determined by the accuracy of the hardware which controls the motion of the camera.

1. Optical Calibration

There is a standard calibration technique known in the field of photogrammetry which is the preferred method of performing the optical calibration of the camera. The technique is discussed, for instance, in the following articles:

"Close-range camera calibration", *Photogrammetric Engineering*, 37(8), 855-866, 1971.

"Accurate linear technique for camera calibration considering lens distortion by solving an eigenvalue problem", *Optical Engineering*, 32(1), 138-149, 1993.

I will outline the equipment and procedure of this calibration here.

The equipment required is a field of calibration target points which are suitable for viewing by the camera to be calibrated. The relative positions of the target points must be known to an accuracy better than that to which

the camera is expected to provide measurements. The number of calibration points should be at least twenty, and as many as several hundred points may be desired for very accurate work.

The calibration target field is viewed with the camera and the image point locations of the target points are determined in the usual way by aligning a video cursor with each point in turn, and commanding the computer to store the measured image point location. The geometry of this process is depicted in Figure 36.

It is important that the relative alignment of the camera and the calibration target field be such as to ensure that target points are located over a range of distances from the camera. If the target field is restricted to being at a single distance from the camera, the determination of the camera effective focal length will be less accurate than otherwise. Another requirement is that targets be distributed with reasonable uniformity over the whole camera field of view. There is no other requirement for alignment between the camera and the target points.

Assume that k target points have been located in the image plane of the camera. The measured coordinates of the jth image point are denoted as (x'_{imj}, y'_{imj}). The following (2 x k) matrix of the measured data is then formed:

$$\mathbf{rho}' = \begin{bmatrix} x'_{im1} & x'_{im2} & \cdots & x'_{imk} \\ y'_{im1} & y'_{im2} & \cdots & y'_{imk} \end{bmatrix} \tag{54}$$

In Figure 36 the vector $\mathbf{r}_{0k}$, which is the (unknown) position of the kth calibration object point in the camera coordinate system, can be written as:

$$\mathbf{r}_{0k} = \mathbf{R}_c(\theta_x, \theta_y, \theta_z)\,[\mathbf{r}_{ck} - \mathbf{r}_c] \tag{55}$$

where $\mathbf{r}_{ck}$ is the known position of the kth calibration point in the calibration target field internal coordinate system (the calibration coordinate system), $\mathbf{r}_c$ is the unknown position of the camera's nodal point in the calibration coordinate system, and $\mathbf{R}_c$ is the unknown rotation of the camera's coordinate system with respect to the calibration coordinate system. As before, rotation matrix $\mathbf{R}_c$ is the product of three individual rotation matrices $\mathbf{R}_z(\theta_z)\mathbf{R}_y(\theta_y)\mathbf{R}_x(\theta_x)$, each of which is a function of a single rotational angle about a single coordinate axis.

The kth ideal image position vector is defined as:

$$\mathbf{rho}_{imk} = \frac{-i}{\mathbf{r}_{0k}(3)} \begin{bmatrix} \mathbf{r}_{0k}(1) \\ \mathbf{r}_{0k}(2) \end{bmatrix} \tag{56}$$

where i is the equivalent focal length of the camera. The (2 x k) ideal image position matrix is defined as:

$$\mathbf{rho}_{im} = [\,\mathbf{rho}_{im1} \quad \mathbf{rho}_{im2} \quad \cdots \quad \mathbf{rho}_{imk}\,] \tag{57}$$

Similarly, the image point coordinate error for the kth point is defined as:

$$\mathbf{rho}_{Dk} = \begin{bmatrix} f_{Dx}(\mathbf{rho}'_k) \\ f_{Dy}(\mathbf{rho}'_k) \end{bmatrix} \tag{58}$$

and the (2 x k) image coordinate error matrix is :

$$\mathbf{rho}_D = [\,\mathbf{rho}_{D1} \quad \mathbf{rho}_{D2} \quad \cdots \quad \mathbf{rho}_{Dk}\,] \tag{59}$$

The error functions f_{Dx} and f_{Dy} define the image location errors which are to be considered in the camera calibration. A number of different error functions are used in the art. The following fairly general expression is given in the article "Multicamera vision-based approach to flexible feature measurement for inspection and reverse engineering", *Optical Engineering*, 32, 9, 2201-2215, 1993:

$$f_{Dx}(\mathbf{rho}'_k) = x_0 + (a_1 + a_2|\mathbf{rho}'_k|^2 + a_3|\mathbf{rho}'_k|^4)x'_{imk} + a_4(|\mathbf{rho}'_k|^2 + 2\,{x'_{imk}}^2) + 2\,a_5\,x'_{imk}y'_{imk} \quad (60)$$
$$f_{Dy}(\mathbf{rho}'_k) = y_0 + (a_6 + a_2|\mathbf{rho}'_k|^2 + a_3|\mathbf{rho}'_k|^4)y'_{imk} + a_5(|\mathbf{rho}'_k|^2 + 2\,{y'_{imk}}^2) + 2\,a_4\,x'_{imk}y'_{imk}$$

where, of course, $|\mathbf{rho}'_k|^2 = {x'_{imk}}^2 + {y'_{imk}}^2$.

The following equation expresses the relationship between the measured image point positions. and the ideal image point positions:

$$\mathbf{rho}' = \mathbf{rho}_{\mathbf{im}} + \mathbf{rho}_{\mathbf{D}} \quad (61)$$

Using the quantities defined above, Equation (61) represents $2k$ equations in 15 unknowns. The unknowns are the three angles of the camera rotation $\theta_z, \theta_y, \theta_x$, the three components of the camera location x_c, y_c, z_c, the equivalent focal length, i, and the eight parameters of image position error $x_0, y_0, a_1, \cdots a_6$. In order to obtain a solution, one must have $k \geq 8$. As I have stated above, one wants to use many more points than this to obtain the most accurate results.

As I previously stated, I call all eight of the image position error parameters "distortion", but only some of them relate to the optical field aberration which is usually referred to as distortion. The parameters x_0 and y_0 represent the difference between the center of the image measurement coordinate system and the position of the optical axis of the camera. Parameters a_1 and a_6 represent different scale factors in the x and y directions. Parameters a_2 and a_3 represent the standard axially symmetric optical Seidel aberration called distortion. Parameters a_4 and a_5 represent possible non-symmetrical distortion due to tilt of the camera focal plane and decentration of the elements in lenses.

The overdetermined set of Equations (61) has no exact solution. Consequently, the calibration data processing determines best fit values for each of the 15 parameters by minimizing the length of an error vector. This is done by an iterative numerical process called non-linear least squares optimization.

Specific algorithms to implement non-linear least squares optimization are well known in the art. They are discussed, for instance, in the book Numerical Recipes by William H. Press, et. al., published by Cambridge University Press, 1st Ed. 1986. This book provides not only the theory behind the numerical techniques, but also working source code in Fortran that is suitable for use in an application program. A second edition of this book is available with working source code in C. Another book which is helpful is R. Fletcher, "*Practical Methods of Optimization, Vol. 1 – Unconstrained Optimization*, John Wiley and Sons, 1980.

A second option for implementation of the non-linear least squares optimization is to use one of the available "canned" numerical software packages such as that from Numerical Algorithms Group, Inc. of Downers Grove, Illinois, USA. Such a package can be licensed and incorporated into application programs, such as the program which controls computer 228. A third option is to use one of the proprietary high level mathematical analysis languages such as MATLAB®, from The Math Works, Inc. of Natick, Massachusetts, USA. These languages have high level operations which implement powerful optimization routines, and also have available compilers, which can produce portable C language code from the very high level source code. This portable C code can then be recompiled for the target system, computer 228.

The optimization process begins with approximate values for the fifteen unknowns and adjusts these iteratively to minimize the quantity:

$$Q = |\mathbf{rho}' - \mathbf{rho}_{\mathrm{im}} - \mathbf{rho}_{\mathrm{D}}|^2 \tag{62}$$

The ideal value of Q is zero; the optimization process attempts to find the smallest possible value.

The starting values for the unknowns are not critical in general, but the iterative process will converge faster if the starting values are not far away from the true values. Thus, it makes sense to perform the optical calibration with a specific alignment of the camera with respect to the calibration target array, so that the camera alignment parameters are approximately already known. It is also a good idea to use any available information about the approximate camera focal length and the distortion parameters in the starting values. For the borescopes I have tried, I have found that terms a_4 and a_5 in Equation (60) are not necessary; in fact, use of them seems to cause slow convergence in the optimization.

The first six calibration parameters, $\{ \theta_z, \theta_y, \theta_x, x_c, y_c, z_c \}$, refer to the position and alignment of the camera as a whole. The other nine parameters are subsequently used to correct measured image point position data to ideal image point position data by:

$$\mathbf{rho}_{\mathrm{im}} = \mathbf{rho}' - \mathbf{rho}_{\mathrm{D}} = \begin{bmatrix} x'_{im} \\ y'_{im} \end{bmatrix} - \begin{bmatrix} f_{Dx}(\mathbf{rho}') \\ f_{Dy}(\mathbf{rho}') \end{bmatrix} \tag{63}$$

which is another way of expressing Equations (22). After the image point positions are corrected, then the visual location vector used in the measurement Equations (27) and (45) is defined as:

$$\mathbf{a}_{\mathrm{v}} = -\frac{1}{i}\begin{bmatrix} \mathbf{rho}_{\mathrm{im}} \\ -i \end{bmatrix} \tag{64}$$

which is a more compact way of expressing Equations (23) and (24).

2. Alignment Calibration

In the perspective measurement process the object of interest is viewed from two points in space, which are called P1 and P2. Recall that the vector connecting the camera nodal point at viewing position P1 to the camera nodal point at viewing position P2 is defined as the perspective displacement **d**. The essence of alignment calibration is to determine the orientation of the perspective displacement, **d**, with respect to the camera's internal coordinate system. Once **d** is known in the camera coordinate system, then the position of object points can be calculated using either Equation (27) or Equation (45), as appropriate.

Since the camera's position and orientation are estimated during the optical calibration procedure given in the previous sub-section, these data can be used to determine the alignment of **d** in the camera's coordinate system if that calibration is done twice, from two different viewing positions. In fact, these are exactly the calibration data that are needed to implement the perspective measurement for a general motion of the camera which was outlined in Equations (42) through (45). All one need do is to carry out the optical calibration procedure at the two measurement camera positions with a fixed calibration target array. This is, in fact, what is done in the photogrammetry field, and is what can be done with a general motion embodiment of my system.

In my preferred embodiments, there is considerable information is available about the motion of the camera that would not be used if one were to proceed as I have just suggested. For instance, if the translation stage is *accurate, then* that means that the orientation of the camera does not change between P1 and P2, and, in fact, it doesn't change for any position of the camera along its path. For those embodiments where the geometry of the

camera path is accurately known, such as the preferred embodiments, one can determine the alignment of $\mathbf{d}$ in the camera's coordinate system at one point on the path and thereby know it for any point on the path.

In addition, the perspective baseline $|\mathbf{d}|$ may be especially accurately known, depending on the performance of the position transducer, and how accurately it is aligned with the motion of the translation stage. As a third possibility, it is possible to accurately measure rotational errors in the translation stage, as long as the motion of the stage is repeatable. All of this information can be taken into account in order to determine a better estimate of the orientation of $\mathbf{d}$ in the camera coordinate system, and thus, to achieve a more accurate measurement.

As a first example of alignment calibration, consider that two optical calibrations have been done at two positions along the camera path, as discussed above. The calibration data available for the camera position and orientation are then $\mathbf{r}_c(\eta_2)$, $\mathbf{r}_c(\eta_1)$, $\mathbf{R}_c(\eta_2)$, and $\mathbf{R}_c(\eta_1)$. Also consider that it is known that the camera moves along an accurate straight line.

The camera orientation in the calibration coordinate system is then estimated as:

$$\mathbf{R}_c = \frac{1}{2}(\mathbf{R}_c(\eta_2) + \mathbf{R}_c(\eta_1)) \tag{65}$$

Note that the difference between $\mathbf{R}_c(\eta_2)$ and $\mathbf{R}_c(\eta_1)$ gives an indication of the precision of this calibration.

The perspective displacement in calibration coordinates is estimated as:

$$\mathbf{d}_g(\eta_2,\eta_1) = \mathbf{r}_c(\eta_2) - \mathbf{r}_c(\eta_1) \tag{66}$$

and in camera coordinates it is estimated as:

$$\mathbf{d}_{v1} = \mathbf{R}_c \mathbf{d}_g(\eta_2,\eta_1) \tag{67}$$

Because there is no rotation of the camera, it is known that the orientation of this vector does not change with camera position.

In Equations (25) and (26) the measurement process was defined in terms of rotation matrices such that:

$$\mathbf{d}_{v1} = \mathbf{R}_z(\theta_z)\,\mathbf{R}_y(\theta_y) \begin{bmatrix} d \\ 0 \\ 0 \end{bmatrix} \tag{68}$$

where $d = |\mathbf{d}_{v1}|$. Writing the measured components of $\mathbf{d}_{v1}$ from Equation (67) as (dv_x, dv_y, dv_z) one writes the following equation, using definitions (35):

$$\mathbf{R}_z(\theta_z)\,\mathbf{R}_y(\theta_y) \begin{bmatrix} d \\ 0 \\ 0 \end{bmatrix} = d \begin{bmatrix} \cos\theta_y \cos\theta_z \\ -\cos\theta_y \sin\theta_z \\ \sin\theta_y \end{bmatrix} = \begin{bmatrix} dv_x \\ dv_y \\ dv_z \end{bmatrix} \tag{69}$$

Equation (69) can be solved for the rotation angles as:

$$\begin{aligned} \theta_y &= \arcsin\left(\frac{dv_z}{d}\right) \\ \theta_z &= \arcsin\left(\frac{dv_y}{\sqrt{dv_x^2 + dv_y^2}}\right) \end{aligned} \tag{70}$$

Thus, the final step of this alignment calibration process is to determine the two angles θ_y and θ_z with Equation (70). During the measurement process, these angles are used in Equation (26).

As a second example of alignment calibration, consider that an optical calibration has been previously done, and now it is desired to do an alignment calibration. This would be the normal situation with the first and second

preferred embodiments, since the alignment of the camera with respect to its translation may change whenever the borescope is clamped to the BPA. Consider also that the motion of the camera is known to be constrained to be along an accurate straight line (that is, any errors in the motion are known to be smaller than the corresponding level of error required of the measurement).

Once again, a calibration target array is viewed from two positions of the camera along its path of motion. According to Figure 36 and Equation (55), one can write:

$$\begin{aligned} \mathbf{r}_{0k1} &= \mathbf{R}_c\left[\mathbf{r}_{ck} - \mathbf{r}_c(\eta_1)\right] \\ \mathbf{r}_{0k2} &= \mathbf{R}_c\left[\mathbf{r}_{ck} - \mathbf{r}_c(\eta_2)\right] \end{aligned} \tag{71}$$

The visual location vectors, which are calculated from the distortion corrected image position data according to Equation (64), can also be written as:

$$\begin{aligned} \mathbf{a}_{vk1} &= \frac{\mathbf{r}_{0k1}}{z_{k1}} = \mathbf{r}_{0k1} u_{k1} \\ \mathbf{a}_{vk2} &= \frac{\mathbf{r}_{0k2}}{z_{k2}} = \mathbf{r}_{0k2} u_{k2} \end{aligned} \tag{72}$$

in terms of the object point coordinates. One corrects the distortion of the measured data using Equation (63) with the distortion parameters obtained in the previous optical calibration.

Define the following quantities where it is assumed that k calibration points are used:

$$\begin{aligned} \mathbf{A}_{v1} &= \left[\mathbf{a}_{v11}\ \mathbf{a}_{v21} \cdots \mathbf{a}_{vk1}\right] \\ \mathbf{A}_{v2} &= \left[\mathbf{a}_{v12}\ \mathbf{a}_{v22} \cdots \mathbf{a}_{vk2}\right] \\ \mathbf{r}_{cal} &= \left[\mathbf{r}_{c1}\ \mathbf{r}_{c2} \cdots \mathbf{r}_{ck}\right] \\ \mathbf{1}_k &= \left[1\ 1 \cdots 1\right] \ (k \text{ components}) \\ \mathbf{U}_1 &= \begin{bmatrix} u_{11} & 0 & \cdots & \cdots & 0 \\ 0 & u_{21} & 0 & \cdots & 0 \\ 0 & 0 & \ddots & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & u_{k1} \end{bmatrix} \\ \mathbf{U}_2 &= \begin{bmatrix} u_{12} & 0 & \cdots & \cdots & 0 \\ 0 & u_{22} & 0 & \cdots & 0 \\ 0 & 0 & \ddots & \cdots & 0 \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & 0 & \cdots & u_{k2} \end{bmatrix} \end{aligned} \tag{73}$$

Then Equations (71) can then be written as:

$$\begin{aligned} \mathbf{A}_{v1} &= \mathbf{R}_c\left[\mathbf{r}_{cal} - \mathbf{r}_c(\eta_1)\mathbf{1}_k\right]\mathbf{U}_1 \\ \mathbf{A}_{v2} &= \mathbf{R}_c\left[\mathbf{r}_{cal} - \mathbf{r}_c(\eta_2)\mathbf{1}_k\right]\mathbf{U}_2 \end{aligned} \tag{74}$$

and Equations (74) can be combined into:

$$\left[\mathbf{A}_{v1} \quad \mathbf{A}_{v2}\right] = \mathbf{R}_c\Big[\left[\mathbf{r}_{cal} \quad \mathbf{r}_{cal}\right] - \left[\mathbf{r}_c(\eta_1)\mathbf{1}_k \quad \mathbf{r}_c(\eta_2)\mathbf{1}_k\right]\Big]\mathbf{U}_{12} \tag{75}$$

where $\mathbf{U}_{12}$ is:

$$\mathbf{U}_{12} = \begin{bmatrix} \mathbf{U}_1 & 0 \\ 0 & \mathbf{U}_2 \end{bmatrix} \tag{76}$$

Equation (75) represents $6k$ equations in $2k + 9$ unknowns, thus, they can be solved for $k \geq 3$. The unknowns are $\mathbf{U}_{12}$($2k$ unknowns) and $\mathbf{R}_c$, $\mathbf{r}_c(\eta_1)$, and $\mathbf{r}_c(\eta_2)$, which each contain 3 unknowns. Equation (75) makes full use of the fact that $\mathbf{R}_c$ is constant: and is thus a more efficient way of estimating the nine unknowns of interest for the alignment calibration than was the previous case.

Equations (75) are solved by a similar nonlinear least squares process as was used for Equation (61). Once the camera positions and orientation are estimated, one simply uses Equations (68) through (70) to determine the alignment angles, which are used during the measurement process.

To improve the efficiency even further, in the case where $d = |\mathbf{d}|$ is considered accurately known, Equations (75) can be solved by a constrained least squares optimization rather than the unconstrained optimization I have so far discussed. Such numerical procedures are discussed in R. Fletcher, "*Practical Methods of Optimization, Vol. 2 -- Constrained Optimization*, John Wiley and Sons, 1980. Most, if not all of the "canned" numerical software offers routines for constrained optimization as well as unconstrained optimization, and so do the high level mathematical analysis languages.

In this case, the constraint is :

$$|\mathbf{r}_c(\eta_2) - \mathbf{r}_c(\eta_1)| - d = 0 \tag{77}$$

It is possible to use an inequality constraint as well, so that if it is known that there is a certain level of uncertainty in the determination of d, then Equation (77) could be replaced with:

$$|\mathbf{r}_c(\eta_2) - \mathbf{r}_c(\eta_1)| - d \leq \epsilon_d \tag{78}$$

where ϵ_d is the known level of uncertainty in d.

As a third example of alignment calibration, I now consider the case where there are rotational errors in the motion of the camera in my third and fourth preferred embodiments. I have already explained how to make the measurement in this case, in the sub-section entitled "Application of the General Process to the Correction of Translation Stage Rotational Errors". In motion calibration sub-section 3. below, I will explain how to determine the rotational errors. Here, I explain how to take these errors into account during the alignment calibration.

For alignment calibration of the EMB or EME with a known stage rotational error, it is necessary to determine the static alignment of the camera with respect to the translation direction in the presence of this error. Recall that at any point along the camera's path :

$$\mathbf{R}_c(\eta) = \mathbf{R}_{cg}\mathbf{R}(\eta) \tag{51}$$

where now $\mathbf{R}(\eta)$ is known from the motion calibration process.

Once again, a calibration target array is viewed from two positions of the camera along its path of motion. According to Figure 36 and Equation (55), one can write:

$$\begin{aligned} \mathbf{r}_{0k1} &= \mathbf{R}_{cg}\mathbf{R}(\eta_1)\,[\mathbf{r}_{ck} - \mathbf{r}_c(\eta_1)] \\ \mathbf{r}_{0k2} &= \mathbf{R}_{cg}\mathbf{R}(\eta_2)\,[\mathbf{r}_{ck} - \mathbf{r}_c(\eta_2)] \end{aligned} \tag{79}$$

These are extended just Equations (71) were to obtain:

$$\begin{aligned} \mathbf{A}_{v1} &= \mathbf{R}_{cg}\mathbf{R}(\eta_1)\,[\mathbf{r}_{cal} - \mathbf{r}_c(\eta_1)\mathbf{1}_k]\mathbf{U}_1 \\ \mathbf{A}_{v2} &= \mathbf{R}_{cg}\mathbf{R}(\eta_2)\,[\mathbf{r}_{cal} - \mathbf{r}_c(\eta_2)\mathbf{1}_k]\mathbf{U}_2 \end{aligned} \tag{80}$$

and Equations (80) can be combined into:

$$[\mathbf{A}_{v1} \quad \mathbf{A}_{v2}] = \mathbf{R}_{cg}\Big[[\mathbf{R}(\eta_1)\mathbf{r}_{cal} \quad \mathbf{R}(\eta_2)\mathbf{r}_{cal}] - [\mathbf{R}(\eta_1)\mathbf{r}_c(\eta_1)\mathbf{1}_k \quad \mathbf{R}(\eta_2)\mathbf{r}_c(\eta_2)\mathbf{1}_k]\Big]\mathbf{U}_{12} \tag{81}$$

which is the same optimization problem as was Equation (75). This is handled exactly the same way to estimate $\mathbf{R}_{cg}$, $\mathbf{r}_c(\eta_1)$, and $\mathbf{r}_c(\eta_2)$. With $\mathbf{R}_{cg}$, the rotation of the camera at any point in its path is known as $\mathbf{R}_c(\eta)$ from Equation (51). I have assumed that the rotation of the stage does not affect the offset of the stage, so that the measurement in this case is accomplished with Equations (49) through (53), Equation (45), and finally Equation (7).

3. Motion Calibration

For the third alignment calibration case above, the rotational errors of the translation stage must have been previously determined in a motion calibration procedure. Preferably, this motion calibration is done at the factory, for a subassembly of the EMB or EME. These calibration data are then incorporated into the software of the complete measurement scope that is constructed using the particular subassembly in question.

The small rotation errors of a linear translation stage can be conveniently measured using a pair of electronic tooling autocollimators as depicted in Figure 37. Each of these autocollimators is internally aligned so that its optical axis is accurately parallel to the mechanical axis of its precision ground cylindrical housing. Such instruments are available from, for example, Davidson Optronics of West Covina, California, USA or Micro-Radian Instruments of San Marcos, California, USA.

In Figure 37, two collimator V - blocks 602 are mounted to a flat stage calibration baseplate 600. The two precision machined V - blocks 602 are located with precision pins so that their axes are accurately perpendicular, to normal machining tolerances. The two V - blocks 602 thus define the directions of a Cartesian coordinate system, which is defined as indicated on Figure 37.

An EMB Subassembly V - block 606 is also mounted to baseplate 600 and located with pins, so that its axis is accurately parallel to the x axis defined by V - blocks 602. Also installed on baseplate 600 is actuator mounting block 608.

The autocollimators 604 are installed into their respective V - blocks and are both rotated about their respective axes so that their measurement y axes are oriented accurately perpendicular to the mounting plate.

With the autocollimators installed and aligned, EMB translation stage subassembly 550 is placed into V - block 606. An enlarged view of a portion of this subassembly is shown in Figure 38. Subassembly 550 consists of distal baseplate 514 (see Figures 21 - 23) to which is mounted translation stage 180, and transducer mounting bracket 367. Translation stage 180 is composed of fixed base 182 and moving table 184. Transducer 360 is mounted in bracket 367, and its operating rod 361 is mounted to transducer attachment bracket 369. Bracket 369 is in turn mounted to moving table 184.

The procedure given here assumes that translation stage 180 has been mounted to distal baseplate 514 so that the axis of translation is oriented parallel to the cylindrical axis of the distal baseplate. This alignment need only be accurate to normal machining tolerances, as I will discuss later. If the specific design of the hardware is different than I show for the preferred embodiment, it is necessary to use some other appropriate method of ensuring that the axis of translation of stage 180 is oriented parallel to the x axis defined by the calibration hardware, and that this orientation is accurate to normal machining tolerances.

Subassembly 550 is rotated about its axis to make the top surface of distal baseplate 514 nominally parallel to baseplate 600 and then it is clamped into position. For purposes of clarity, the clamp is not shown in Figure 37.

Stage operating arm 614 is then attached to moving table 184. Actuator 610 is installed in mounting block 608, and actuator operating rod 612 is attached to operating arm 614. Thus, the stage can now be moved back and forth over its range of travel and a function of its position, $\eta(p)$, can be read at the output of position transducer 360.

Stage 180 is moved to the mid range of its travel by the use of actuator 610. Mirror platform 618 is then attached to moving table 184. Mirror platform 618 has mounted to it two mirror mounts 620, which in turn hold a longitudinal mirror 622 and a transverse mirror 624.

Mirror mounts 620 are then adjusted to tilt each of the mirrors in two angles so as to center the return beams in autocollimators 604 as determined by the angular readouts of the autocollimators (not shown).

Translation stage 180 is then moved to one end of its travel using actuator 610. Calibration data are then recorded by moving stage 180 toward the other end of its travel range in a series of suitably small steps in distance. The output of position transducer 360, η, is recorded at each step position, as are the angular readings of the autocollimators. Note that one need not be concerned with the actual distance stage 180 is moved between steps, unless one is also intending to calibrate transducer 360 at the same time.

The readings from the autocollimator viewing along the x axis will be $(2\,\theta_y,\ 2\,\theta_z)$, where the positive direction for the angles is counter-clockwise when the view is along the axis from positive coordinates toward the origin (i.e., the right hand rule). The readings from the autocollimator viewing along the z axis will be $(2\,\theta_y,\ -2\,\theta_x)$. The rotational error of the stage at any point can be expressed as:

$$\mathbf{R}(\eta) = \mathbf{R}_z(\theta_z)\mathbf{R}_y(\theta_y)\mathbf{R}_x(\theta_x) \tag{82}$$

It is more efficient to record and store the three angles $\theta_z(\eta), \theta_y(\eta), \theta_x(\eta)$ and calculate $\mathbf{R}(\eta)$ whenever it is needed. When the calibration data are used in a measurement procedure, it will be necessary to interpolate between the stored values of η to estimate the rotation angles at the actual values of η used in the particular measurement. Such interpolation procedures are well known in the art.

An error analysis shows that the angles measured during this calibration process will be a mixture of the components of the true rotational angles, if the calibration geometry is not perfectly aligned with the translation direction of the stage. However, the level of the mixed components is proportional to the error in the geometry, and thus will be small. For instance, if the angles determining the calibration geometry were all in error by three degrees (which is much larger than one would expect, using normal machining tolerances), the measured stage rotation angles would be 10% in error in the worst case. Since it is unlikely that the repeatability of a translation stage will be much more than ten times better than its absolute angular accuracy, this level of error is appropriate for calibration of the stage angular errors. Thus, use of a calibration geometry which is determined by precision machining is adequate to perform the calibration measurements.

M. Eliminating Routine Alignment Calibrations in BPA Embodiments

There is an inconvenience with the first and second embodiments as taught above, which is that a new alignment calibration might have to be performed each time a new measurement situation is set up. In alignment calibration, the orientation of the borescope's measurement coordinate system with respect to the motion provided by the BPA is determined. With a standard borescope, this orientation may not be well controlled, and thus every time the borescope is repositioned with respect to the BPA, there is the logical requirement for a new alignment calibration. Of course, whether a new calibration would actually be required in any specific instance depends on the accuracy required of the dimensional measurement in that instance. And of course, whether or not avoiding the inconvenience of the requirement for routine alignment calibrations is worth the additional structure and procedure described here will be determined solely by the user's application.

I describe here modifications to the borescope, to the BPA, and to the calibration and measurement procedures which work together to eliminate the need for routine alignment calibrations in borescope/BPA embodiments of my perspective measurement system. The user of my system may select from one of the subsequently described combination of modifications as required to improve the accuracy of the measurements made and/or to make the system more convenient to use.

1. Detailed explanation of the problem

A first difficulty with the first and second embodiments of my system is depicted in Figure 39. Here, the lens tube of the borescope is not perfectly straight. Thus, when the borescope is clamped to the BPA at different points along its length, the geometrical relationship between the perspective displacement **d** and the visual coordinate system changes. This means that, for accurate work, an alignment calibration must be performed whenever the borescope is clamped at different positions along its length.

A second difficulty is depicted in Figures 40A and 40B. Coordinate axes parallel to the visual coordinate system are drawn in Figure 40 to make it easier to visualize the geometrical relationships. In these Figures the borescope is shown aligned along a mechanical axis (A - A). The Figure is drawn in the plane which contains the mechanical axis and which is also parallel to the perspective displacement **d**.

In Figure 40B the borescope has been rotated by 180 degrees about the mechanical axis with respect to its position in Figure 40A. In Figure 40A, the component of the visual x axis that is perpendicular to the page is directed into the page. In Figure 40B, the component of the visual x axis that is perpendicular to the page is directed out of the page.

The orientation of **d** with respect to the visual coordinate system is not the same in Figures 40A and 40B. (This may be most clear when considering the visual z axis.) Thus, when the axis of mechanical rotation of the borescope is not parallel to the perspective displacement, the orientation of the perspective displacement in the visual coordinate system will change when the borescope is rotated about that mechanical axis. For the system shown in Figures 4 and 5, the mechanical axis of rotation is determined by the V groove of lower V block 142 of the BPA. This means that an alignment calibration must be performed whenever the borescope is clamped at a new angular orientation with respect to the BPA, unless the V groove is accurately aligned along the translation axis of the translation stage.

A third difficulty is caused by the characteristics of the lens tube of a standard borescope. The envelope of the lens tube is typically made of thin wall stainless steel tubing. Such an envelope is unlikely to be perfectly circular

at any position along its length, and it has already been discussed how unlikely it is to be straight. Rotation of such a geometrically imperfect envelope in a V groove will lead to a varying orientation of **d** with respect to visual coordinates even if the V groove were aligned with **d** and the clamping position along the length tube were unchanged. Once again, the situation is that if the borescope is moved with respect to the BPA, then alignment calibration must be repeated, at least for accurate work.

One approach to addressing these problems would be to characterize the alignment of the perspective displacement with respect to the visual coordinate system as a function of the position and orientation of the borescope with respect to the BPA. While this would work in theory, the amount of calibration effort necessary and the likelihood of poor repeatability of borescope orientation, due to the characteristics of the lens tube envelope, make this approach unattractive.

2. Description of a First Variant of Borescope/BPA Embodiments

Figure 41 shows a first modification to my BPA embodiments which solves these problems. In Figure 41, clamp 140 is shown in the open position in order to better show the modifications.

A portion of borescope lens tube 124 has been enclosed by a *metrology sleeve* or *calibration sleeve* 650. Calibration sleeve 650 is comprised of a thick-walled cylindrical tube 652 with sleeve ferrules 654 attached at either end. Sleeve nuts 656 screw on to ferrules 654 to clamp the assembly to lens tube 124 at any selected position along lens tube 124.

The outer diameter of cylindrical tube 652 is fabricated to be accurately circular and straight. This is typically done by a process known as centerless grinding. Tube 652 is preferably made of a rather hard material, for instance high carbon steel coated with hard chrome, or case-hardened stainless steel. On the other hand, upper V block 144 is preferably made of a somewhat softer material, for instance, low carbon steel, aluminum, or brass. Because of these relative hardnesses, and because of the thick wall of tube 652, it is no longer necessary to use a layer of resilient material to line upper V block 144, and thus it is not shown in Figure 41. This also means that a much higher clamping pressure can be used in this system than could be used in the original system of Figure 4.

Calibration sleeve 650 lies in the V groove in lower V block 142. The dimensions of the V grooves in both lower V block 142 and upper V block 144 have been modified from those shown in previous figures in order to clamp the larger diameter of tube 652. In order for the groove in lower V block 142 to act as the position reference for sleeve 650, and hence, ultimately, for video borescope 120, hinge 148 is now fabricated with an appropriate amount of play, so that the groove in upper V block 144 takes a position and orientation which is determined by sleeve 650 when clamp 140 is closed.

The groove in lower V block 142 is accurately aligned to the translation axis of stage 180 to a predetermined tolerance using one of the methods to be described later.

An alternative embodiment of a calibration sleeve is shown in Figure 42. There a strain-relieving calibration sleeve 660 is shown attached to video borescope 120. At the distal end, sleeve 660 is attached to borescope lens tube 124 with the same ferrule (654) and nut (656) system that was shown in Figure 41. At the proximal end, sleeve 660 is attached to the body of the endoscope through a torque transferring clamping collar 658. In the embodiment that was shown in Figure 41, the overhanging torque due to the proximal (rear) portion of borescope 120 is concentrated on the small diameter lens tube 124 at the point at which lens tube 124 exits ferrule 654. Video endoscope systems vary in the size and weight of their proximal portions, and it is probable that in some

cases, the overhanging torque will exceed the capacity of lens tube 124 to resist bending. In this alternative embodiment, collar 658 transfers this torque to a more robust portion of the endoscope. As shown in Figure 42, with the generic video borescope 120, collar 658 is securely clamped to illumination adapter 126; this clamping can be done with any of several common and well-known techniques. Collar 658 is constructed so as to provide the necessary operating clearance for fiber optic connector 128. Depending on the design of the borescope being used, it may be that some other portion of the borescope will be the most suitable attachment point for collar 658.

3. Operation of the First Variant of Borescope/BPA Embodiments

Consider Figure 41 once again. In use, calibration sleeve 650 is semi-permanently attached to borescope 120. When nuts 656 are tightened, sleeve ferrules 654 grab tightly without marring or denting the surface of lens tube 124, fixing the relative locations of lens tube 124 and the outer cylindrical surface of sleeve 650. Since the visual coordinate system is fixed with respect to the outer envelope of the borescope, the outer surface of sleeve 650 is fixed with respect the visual coordinate system. I call the assembly of borescope 120 and calibration sleeve 650 the *perspective measurement assembly*.

The perspective measurement assembly can be located at any position inside clamp 140, and can be clamped in that position, as long as a significant length of sleeve 650 is contained within the clamp. The action of placing sleeve 650 in the V groove in lower V block 142 constrains four degrees of freedom of the motion of sleeve 650. The two unconstrained motions are rotation about the axis of the sleeve, and translation along that axis. Translation is, of course, limited to a range of distances over which a significant length of the sleeve will be contained inside the clamp. Since the borescope is clamped inside the sleeve, its motion is similarly constrained and controlled, as is the motion of the visual coordinate system. These two degrees of freedom are precisely those necessary to allow borescope 120 to view objects at different positions with respect to BPA 138 (Figure 4).

Since the groove in lower V block 142 is accurately aligned with the translation axis of stage 180, and since the outer surface of sleeve 650 is accurately cylindrical, the relative orientations of **d** and the visual coordinate system do not change as the perspective measurement assembly is rotated or translated in lower V block 142. Note that there need be no particular orientation of the visual coordinate system with respect to the axis of the cylindrical outer surface of sleeve 650. The only requirements for there to be a constant relative orientation between **d** and the visual coordinate system are that the surface of sleeve 650 be accurately cylindrical, and that the axis of the locating V groove be accurately directed along **d**.

For making measurements on objects at widely differing depths inside enclosure 110 (Figure 4), sleeve 650 can be moved on lens tube 124, but when it is moved, a new alignment calibration will be required, in general. The range of depths that can be accommodated by a perspective measurement assembly without recalibration is determined by the length of sleeve 650. For many users a limited range of available measurement depths is not a problem because their objects of interest are confined to a small range of depths inside the enclosure.

Calibration sleeve 650 could be made nearly as long as lens tube 124. This suggests another option for eliminating the need for routine alignment calibrations. I call this option the *metrology borescope*. A metrology borescope, a new instrument, is a rigid borescope built with a lens tube which is thicker, stiffer, and harder than normal. The outer envelope of lens tube 124 of a metrology borescope is precision fabricated to be accurately cylindrical. Such a scope does not need calibration sleeve 650 in order to provide accurate perspective dimensional measurements with only a single alignment calibration.

Standard borescopes, with their thin envelopes, tend to get bent in use. A small bend does not ruin a borescope for visual inspection, but it would ruin the accuracy of any calibrated perspective measurement assembly. Since the metrology borescope is more resistant to such bending, it is the superior technical solution.

An additional advantage of the system shown in Figure 41 over that shown in Figure 4 is that borescopes with different lens tube diameters can be fitted with appropriate calibration sleeves of the same outer diameter. Thus, when the calibration sleeve is placed into lower V block 142, the centerline of the borescope is always at the same position with respect to the BPA, which is not the case when different diameter borescopes are directly inserted into the V block. Keeping this centerline at a constant position makes the mounting of the BPA with respect to enclosure 110 and inspection port 112 (Figure 4) less complicated when borescopes of different diameters are to be accommodated.

I have already stated that the V groove in lower V block 142 is accurately aligned with the translation axis of translation stage 180. I now explain exactly what this means, and then how that condition can be achieved.

A V groove is made up of two bearing surfaces which, ideally, are sections of flat planes. If these surfaces are perfect, then the corresponding planes will intersect in a straight line. It is when this line of intersection is parallel to the translation axis of stage 180, that it can be said that the V groove is accurately aligned with the translation.

The purpose of the V groove is to locate the cylindrical outside diameter of the calibration sleeve accurately and repeatably. By locating a cylindrical object accurately, I mean that for a short section of a perfect cylinder, the orientation of the axis of the cylindrical section does not depend on where along the length of the V groove the cylindrical section happens to bear, and that there is a continuous single line contact between each bearing surface and the cylindrical section, no matter where that section happens to lie along the V groove, and no matter how long that section is.

A V groove will serve to locate a cylindrical object accurately even if the bearing surfaces are not planar, just so long as three conditions hold. First, each of the bearing surfaces must either have a symmetry about a straight line axis or must be perfectly planar. Second, the straight line axis of one surface must be parallel to the axis or plane of the other surface. Third, surfaces with symmetry about a straight line axis must either be convex or have a sufficiently large radius of curvature that there is only one line of contact between the cylindrical object and the surface.

This means, for instance, that two accurately cylindrical bodies can serve to accurately locate a third cylinder just as long as the axes of the first two cylinders are parallel, and such a system could be used instead of the preferred V groove.

It is also possible to form two physical lines of contact, by cutting a cylindrical groove into a plane surface or into a larger radius cylindrical groove, for example. These physical lines can serve to accurately locate a cylinder, but only if the cylindrical groove is oriented accurately parallel to the plane surface or cylinder into which it is cut. If the cylindrical groove is not so oriented, the contact lines formed thereby will not be straight and will not serve to accurately locate a cylindrical body.

In order to locate the calibration sleeve repeatably, it is necessary to pay appropriate attention to maintaining the cleanliness of both the outer surface of the calibration sleeve and of the locating surface on the BPA, whether that surface is embodied as a V groove or as some other appropriate geometry.

To maintain the accuracy of the perspective measurement, one must maintain the orientation of the visual coordinate system with respect to the outer surface of the calibration sleeve, and one must also maintain the alignment of the BPA reference surface with respect to the perspective displacement. In order to maintain these geometrical relationships over a wide range of operating temperatures, one must pay careful attention to the effects of differential thermal expansion, especially in those embodiments which use an alignable BPA reference surface.

4. How to Achieve Accurate Alignment of the BPA Reference Surface

In any discussion of "accuracy" must include a definition of the size of errors which are allowed while still justifying the label "accurate". In my perspective measurement system, the error of interest is the error in the dimensional measurement being made. As far as the alignment of the system is concerned, an unknown error in the orientation of **d** with respect to the visual coordinate system will cause a systematic error in the distance measurement.

Analysis shows that a misalignment of **d** will cause a systematic measurement error which will vary linearly with the distance (range) between the object being measured and the nodal point of the borescope optical system. That is, this systematic error in a distance measurement can be expressed as a fraction of the range to the object, for example, 1 part in 1000, or as an error angle, e.g. 1 milliradian. In detail, the error in any given measurement depends on the position of the object in the apparent field of view of the borescope in each of the two views, and on the fractional portion of the field of view subtended by the distance being measured.

In the worst case, the error in the measured distance is approximately equal to the angular error in the orientation of **d** times the range to the object. That is, a 1 milliradian angular error in the orientation of **d** corresponds approximately to a worst case distance measurement error of 1 part in 1000 of the range.

A given level of acceptable systematic measurement error will correspond to an acceptable level of misalignment. For the purposes of this discussion, I will define two levels of acceptable error. I call a "Class 1" measurement one that is accurate to 1 part in 1000 of the range. I call a "Class 2" measurement one that is accurate to 1 part in 10,000 of the range. These acceptable error levels are consistent with the random error capabilities of the perspective measurement system when it is implemented with standard endoscopy equipment. A random error of 1 part in 1000 of the range is fairly straightforward to achieve using a standard video borescope, while achieving 1 part in 10,000 random error requires either (1) the use of a high resolution borescope optical system and a high resolution video camera back and some averaging of measurements, or (2) the averaging of a large number of measurements.

The achievement of a misalignment of 1 millirad, i.e., 0.001 cm. per cm., is straightforward by use of precision machining techniques, as long as translation stage 180 has been fabricated with accurate mechanical references to its translation axis. If it has not been so fabricated, one proceeds as follows.

Usually, the top surface of moving table 184 of stage 180 (Figure 5) is guaranteed by the manufacturer to be parallel to the translation to within a specified tolerance. Often, this tolerance is 0.1 milliradian. If the top of the moving table has not been accurately aligned with the translation, then one can measure the pitch of the top surface by suspending a dial indicator above the stage and indicating on the top surface of moving table 184 as it translates below. This known pitch can then be compensated for in the machining of lower V block 142.

If there is not a convenient reference for the direction of the translation axis as measured in the plane of the top surface of moving table 184, suitable reference holes are easily made by mounting the stage on a drilling machine and using the motion of the stage itself to determine the relative positions of the holes.

Once stage 180 has been characterized and/or modified, lower V block 142 is fabricated with standard machining techniques while paying particular attention to two key factors. First, the bottom surface of lower V block 142 must be oriented accurately parallel to the translation axis of the fabrication machine when the V groove is cut into its upper surface (or tilted to offset the pitch of the top of moving table 184, measured as discussed immediately above). Secondly, the V groove, and any reference holes, are machined with a fixed tool spindle location and with the machine tool moving lower V block 142 only along a single translation axis. This guarantees that the V groove will be parallel to the line between the centers of the reference holes to an accuracy determined by the straightness of the machine tool translation axis.

The achievement of a misalignment appropriate to Class 2 measurements, i.e. 0.1 milliradian, by precision machining is possible, but difficult and expensive. One way to make it more feasible is to do the final grinding of the V groove into block 142 with block 142 mounted to the translation stage. The stage motion itself is used to provide the necessary motion of the block with respect to the grinding wheel. The disadvantage of this approach is that the length of the V groove is limited to somewhat less than the length of travel of the stage. The advantage is that the alignment of the V groove with the translation will be accurate to within the accuracy of translation of the stage.

For Class 2 accuracy, it may be preferable to align the V with respect to the translation of the stage. One way to accomplish this alignment is to use shims to adjust the position of lower block 142 in pitch with respect to the top of moving table 184 and in yaw with respect to a reference surface attached to the table top. A second way is to split lower block 142 into two plates with a variable relative alignment in pitch and yaw. Such a device would be similar to and work on the same principles as the Model 36 Multi-axis Tilt Platform sold by the Newport Corporation of Irvine, CA, USA. The upper plate of this assembly is steered with respect to the lower plate in pitch and yaw through the use of adjusting screws, while the lower plate is conventionally attached to the top of moving table 184.

A rig for determining the alignment of the V groove to the translation of the stage is depicted in Figure 43. Here is shown a front elevation view of a translation stage 180, to which is attached a split lower V block 143. Split lower V block 143 is constructed as discussed in the previous paragraph. As before, upper V block 144 acts as a clamp; the screw or mechanism which provides clamping force is not shown. A reference cylinder 700 is clamped into split lower V block 143 so that a suitable length of cylinder 700 extends out of the clamp towards the observer. Reference cylinder 700 is selected to be straight and circular to a very high degree of accuracy. A pair of dial indicators 702 are mounted to the work surface by conventional means which are not shown. Indicators 702 are suspended over reference cylinder 700 and disposed to either side of it. Sensing feet 704 of dial indicators 702 contact the shaft at the same distance from the clamp as measured along cylinder 700. Sensing feet 704 have a flat surface over most of their diameter in order to avoid errors due to the imperfect alignment of the indicator measurement axis with the axis of reference cylinder 700.

To determine the desired alignment, stage 180 is translated back and forth along its length of travel, and the readings of the dial indicators are monitored. Errors in pitch of the V groove are indicated by changes in the

average of the two dial indicator readings. Errors in yaw are indicated by changes in the difference of the two readings. The alignment of the V groove is perfect when the dial indicators do not change as the stage is translated.

The arrangement of dial indicators 702 is not restricted to that shown in Figure 43. One could orient one of the indicators so that it was suspended vertically above reference cylinder 700, and the other could be oriented horizontally. Then one indicator would directly indicate pitch, while the other would directly indicate yaw. The only requirement is that the two indicators not be oriented in exactly the same direction, and for best sensitivity and most convenience, there should be a right angle between their orientations.

One can check for the presence of geometrical imperfections in the combination of reference cylinder 700 and the V groove in lower V block 143 by loosening the clamp, rotating reference cylinder 700 about its axis to another angular position, tightening the clamp, and redoing the check. One can also repeat the test at different positions along the length of cylinder 700 to check for errors in its straightness. A good reference for the theory and practice of making such measurements is *Handbook of Dimensional Measurement, 2nd Edition*, by Francis T. Farago, Industrial Press, New York, 1982.

One could directly indicate on the plane surfaces of the V groove rather than using a reference cylinder as I have shown. But in that case, one would be measuring imperfections in these surfaces as well as their alignment, when what one really cares about is how the existing V groove acts to locate a cylinder. Since accurate reference cylinders are readily available, I prefer the method I have shown.

Of course, it must be kept in mind that one cannot expect to determine errors in the geometry of cylinder 700 or in the V groove in lower V block 143 to a level better than that provided by the straightness and repeatability of motion of translation stage 180. Since the purpose of this test rig is to align the V groove with respect to this motion, errors in this motion do not affect the validity of the results.

One can check for the integrity of the rotation of a cylinder in a V block by mounting a mirror on an adjustable mirror mount so that the mirror is approximately perpendicular to and centered on the axis of the cylinder. This process is depicted in Figure 44. In Figure 44 a laser 710 produces a laser beam 716. Laser beam 716 is reflected from a mirror which is part of mirror mount assembly 712. The beam reflected from the mirror is allowed to impact a viewing screen 714.

The mirror mount is adjusted to produce the smallest motion of the laser spot as the cylinder is rotated in the V block. Any residual motion of the spot, which cannot be reduced by adjustment of the angular orientation of the mirror, is due to non-constant angular orientation of the cylinder as it rotates while maintaining contact with the V block. The variation of the orientation of the axis of the cylinder can be sensed to within a few tenths of a milliradian in this way. A sensitivity on the order of a microradian can be achieved, once the mirror has been aligned as shown here, by viewing the mirror with an autocollimator which has been aligned nearly perpendicular to the mirror, and again rotating the cylinder.

It is possible to conceive of a motion of the cylinder in the V block that is not perfect, but is such that the mirror remains at a constant angular orientation while the cylinder is being rotated. (One way is for the cylinder to *wobble as it* rotates.) What is important about such a situation is that any motion which causes an error in the perspective measurement will also cause an error when being tested by the technique depicted in Figure 44.

5. Description of a Second Variant of Borescope/BPA Embodiments

A second modification to BPA embodiments is shown in Figure 45. This differs from the first modification in that there is now an angle scale or protractor 670 attached to cylindrical tube 652. A protractor pointer 672 is attached to a pointer mounting bar 673 which is in turn attached to lower V block 142. Pointer 672 has sufficient length to enable the angular orientation of the perspective measurement assembly to be determined no matter where it is located in its range of translation with respect to clamp 140.

In this embodiment, the V groove in lower block 142 need not be accurately aligned with the perspective displacement.

Another option would be to use the strain-relieving calibration sleeve 660 as depicted in Figure 42. Then an angular scale could be advantageously marked on the outer diameter of collar 658.

6. Operation of the Second Variant of Borescope/BPA Embodiments

It was shown in Figure 40 that the alignment of the perspective displacement, **d**, in the visual coordinate system is a function of the rotation of the perspective measurement assembly about the axis of the cylindrical surface of the calibration sleeve. In this second embodiment, the acquisition of an additional piece of information during the measurement, and an additional step in alignment calibration, enable one to calculate the alignment of **d**, and thus make an accurate perspective measurement, despite the presence of a misalignment between the axis of the calibration sleeve and the perspective displacement. I will explain the operation of the measurement in this section, and the necessary additional calibration of the system in the next section.

Figure 46 is similar to Figure 40 but it contains additional information. As before, a visual coordinate system (x_v, y_v, z_v) is defined by the x and y axes of the video camera focal plane, and the optical axis of the borescope. In Figure 46 coordinate axes parallel to the visual coordinate system are shown in the field of view of the borescope. As before, the Figure is drawn in the plane which contains the axis of mechanical borescope rotation, A-A, and which is parallel to the perspective displacement, **d**. None of the visual coordinate axes x_v, y_v, z_v are necessarily contained in the plane of the Figure. Again as before, in Figure 46A, the component of the visual x axis that is perpendicular to the page should be visualized as being directed into the page, while it should be visualized as being directed out of the page in Figure 46B.

One may define a borescope mechanical coordinate system which rotates with the borescope, which has a fixed relationship with respect to the visual coordinate system, and which has its x axis parallel to A-A as follows:

(1.) The x_m axis is oriented along A-A.

(2.) The y_m direction is chosen to be perpendicular to both the optical axis, z_v, and to x_m. This can be expressed mathematically as:

$$\hat{\boldsymbol{y}}_m = \frac{\hat{\boldsymbol{z}}_v \times \hat{\boldsymbol{x}}_m}{|\hat{\boldsymbol{z}}_v \times \hat{\boldsymbol{x}}_m|} \tag{83}$$

(3.) Finally, the z_m axis is chosen to be perpendicular to both x_m and y_m axes in the usual way as:

$$\hat{z}_m = \frac{\hat{\boldsymbol{x}}_m \times \hat{\boldsymbol{y}}_m}{|\hat{\boldsymbol{x}}_m \times \hat{\boldsymbol{y}}_m|} \tag{84}$$

The mechanical coordinate system (x_m, y_m, z_m) is depicted in Figure 46. One important implication of this definition is that the optical axis, z_v, is guaranteed to lie in the (z_m, x_m) plane.

Also shown in Figure 46 is a translation coördinate system, (x_t, y_t, z_t), which has a fixed orientation with respect to the translation stage. The x_t axis is defined to lie along the perspective displacement, **d**. For the moment, the directions of the y_t and z_t axes are taken to be arbitrary, but the (x_t, y_t, z_t) system is defined to be a conventional right-handed Cartesian coordinate system.

For the purposes of this discussion, all of these coordinate systems will be assumed to have origins at the same point in space, although they are drawn separated in Figure 46 for clarity.

What one needs is an expression for **d** in the visual coordinate system. This expression will depend on the rotation of the borescope about the mechanical axis A-A. The parameter for this rotation is taken to be the angle ϕ_x.

As mentioned previously with regard to the general perspective measurement process, in order to discuss rotations in three dimensions, one must carefully define what procedure is being used for a series of sub-rotations. I define the specific procedure for rotating the mechanical coordinate system to align it with the translation coordinate system as follows:

(a.) Rotate the m coordinate system about x_m until y_m lies in the (x_t, y_t) plane.

(b.) Rotate the m coordinate system about y_m until z_m coincides with z_t.

(c.) Rotate the m coordinate system about z_m until x_m coincides with x_t (and y_m coincides with y_t).

Mathematically, this procedure can be expressed as:

$$\mathbf{v}_t = \mathbf{R}_z(\phi_z)\mathbf{R}_y(\phi_y)\mathbf{R}_x(\phi_x)\,\mathbf{v}_m = \mathbf{R}\,\mathbf{v}_m \tag{85}$$

where the 3 × 3 matrices **R** have been defined in Equations (33-35). In Equation (85), $\mathbf{v}_t$ and $\mathbf{v}_m$ are 3 × 1 matrices which contain the components of any arbitrary vector as expressed in the translation and mechanical coordinate systems respectively. The angles ϕ_x, ϕ_y, and ϕ_z are the angles by which the coordinate system is rotated in each step of the procedure. At each step, the angle is measured in the coordinate system that is being rotated. The positive direction of rotation is defined by the right hand rule.

Step (a.) of the procedure implicitly states that $\phi_x = 0$ when y_m lies in the (x_t, y_t) plane. In the embodiment shown in Figure 45, the orientation of the perspective measurement assembly for which $\phi_x = 0$ is defined by the scale on protractor 670. Together, these two facts mean that it is the location of the zero point on the scale of protractor 670 which defines the orientation of the y_t and z_t axes. The orientation of these axes can no longer be considered arbitrary.

The inverse transformation to Equation (85), that is, the procedure for rotating the translation coordinate system to align it with the mechanical system, can be expressed as:

$$\mathbf{v}_m = \mathbf{R}_x(-\phi_x)\mathbf{R}_y(-\phi_y)\mathbf{R}_z(-\phi_z)\,\mathbf{v}_t = \mathbf{R}_x^{-1}(\phi_x)\mathbf{R}_y^{-1}(\phi_y)\mathbf{R}_z^{-1}(\phi_z)\,\mathbf{v}_t \tag{86}$$

Recall that the mechanical coordinate system was defined so that the visual z axis is confined to the mechanical (x, z) plane. The relationship of the visual and mechanical coordinate systems is depicted in Figure 47. *Because of* the way the relationship between these two coordinate systems was defined, there are only two rotation angles necessary to align one with the other. The specific procedure for rotating the mechanical coordinate system so that it is aligned with the visual coordinate system is simply:

(a.) Rotate about the mechanical y axis by angle θ_y.

(b.) Rotate about the mechanical z axis by angle θ_z.

In mathematical terms this is:

$$\mathbf{r}_v = \mathbf{R}_z(\theta_z)\mathbf{R}_y(\theta_y)\,\mathbf{r}_m \tag{87}$$

Angle θ_y represents a rotation of the optical axis with respect to the mechanical z axis; this rotation is confined to the mechanical (x, z) plane. Angle θ_z represents a rotation of the visual coordinate system about the optical axis.

Combining Equations (86) and (87), one can express the relationship between a vector as expressed in the translation and visual coordinate systems as:

$$\mathbf{r}_v = \mathbf{R}_z(\theta_z)\mathbf{R}_y(\theta_y)\,\mathbf{R}_x^{-1}(\phi_x)\mathbf{R}_y^{-1}(\phi_y)\mathbf{R}_z^{-1}(\phi_z)\,\mathbf{r}_t \tag{88}$$

Since the displacement vector, as expressed in translation coordinates is simply $\mathbf{d} = d\begin{bmatrix}1\\0\\0\end{bmatrix}$, one has:

$$\mathbf{d}_v = \mathbf{R}_z(\theta_z)\mathbf{R}_y(\theta_y)\,\mathbf{R}_x^{-1}(\phi_x)\mathbf{R}_y^{-1}(\phi_y)\mathbf{R}_z^{-1}(\phi_z)\begin{bmatrix}d\\0\\0\end{bmatrix} \tag{89}$$

Therefore, to determine the three-dimensional position of a point of interest with this second modification, one determines the visual location vectors $\mathbf{a}_{v1}$ and $\mathbf{a}_{v2}$ as usual. One also records the reading of protractor 670 as indicated by pointer 672. This is the angle ϕ_x. One then uses the four angles (θ_z, θ_y, ϕ_y, ϕ_z) as determined in an alignment calibration, in Equation (89) to determine the displacement vector as expressed in visual coordinates. This alignment calibration is discussed below. Finally, one uses Equation (19) to determine the position of the point.

There are many other ways that the rotation of the perspective measurement assembly with respect to the BPA could be determined. For instance, the rotation could be sensed with an optical or an electrical transducer, and the user would then avoid having to read a scale manually. It is also possible to attach the protractor to the BPA and the pointer to the perspective measurement assembly to achieve the same result as does the preferred embodiment shown in Figure 45. In addition, the angle scale could be read more precisely when necessary by using a conventional vernier scale index instead of the simple pointer 672.

It is important to consider how accurately one must determine ϕ_x in order to achieve the accuracy desired in the perspective measurement. Assume that the misalignment of the mechanical x axis with respect to the translation x axis is small enough that the sines of the angles ϕ_y and ϕ_z can be replaced with the angles themselves. Then it can be calculated, by differentiation of Equation (89), that the worst case error component in $\mathbf{d}_v/d$ is $\sqrt{\phi_y^2 + \phi_z^2}$ times the error in ϕ_x. If we take ϕ_y and ϕ_z to have equal magnitudes, and call that magnitude $\phi_\perp$, then the worst case error component in $\mathbf{d}_v$ is $\sqrt{2}\,\phi_\perp\Delta\phi_x$. Thus, any combination of misalignment, $\phi_\perp$, and rotational measurement error, $\Delta\phi_x$, that forms the same product will create the same level of systematic error in the perspective measurement.

As an example, assume that the misalignment of the mechanical x axis with respect to the translation is 10 milliradians (0.57 degrees), a value easily achieved with non-precision fabrication techniques. In this case, to

achieve a perspective measurement to Class 1 accuracy (1 part in 1000 of the range) the allowable error in the rotation of the perspective measurement assembly is 71 milliradians, or 4.1 degrees. For Class 2 accuracy under the same conditions, the measurement of the rotation must be ten times more accurate.

7. Calibration of a System using the Second Modification

In the discussion of calibration above, it was shown how to calibrate both the optical parameters of the borescope, and the relative alignment of the visual and translation coordinates. The assumption there was that the mechanical x axis was directed exactly along the translation direction or that there would be no rotation of the borescope between calibration and measurement. The alignment calibration determines the two alignment angles θ_z and θ_y of the translation with respect to the visual coordinate system.

If borescope is translated from one viewing position to a second viewing position, and if the location of the nodal point is determined in the same calibration coordinate system at both positions, then the alignment of the displacement vector in the visual coordinate system can be determined from Equation (67) as:

$$\mathbf{d}_v = \mathbf{R}_c\,[\,\mathbf{r}_c(\eta_2) - \mathbf{r}_c(\eta_1)\,] \tag{90}$$

where η_1 and η_2 are parameters denoting the translation position at the first and second viewing positions. Equation (90) expresses the standard alignment calibration process. The result is specific to the particular orientation, ϕ_x, that the perspective measurement assembly has during the alignment calibration, if the mechanical axis of rotation of the perspective measurement assembly is not aligned with the perspective displacement.

To perform the alignment calibration for a system using the second modification, this standard process is performed twice, with the perspective measurement assembly being rotated in the clamp of the BPA between these two alignment calibrations.

The preferred rotation between the two alignment calibrations is approximately 180 degrees. In other words, a standard alignment calibration is performed with, for instance, the calibration target array serving as the object of interest in Figure 4. Then, the perspective measurement assembly is rotated 180 degrees inside the clamp of the BPA and the calibration target array is moved to the other side of the BPA so that the targets can again be viewed, and a second alignment calibration is performed.

In terms of the rotation angles defined in Equations (86) and (87) one can write the directions of the perspective displacements in the visual coordinates for these two alignment calibrations as:

$$\begin{aligned}\mathbf{d}_{uA} &= \frac{\mathbf{d}_{vA}}{|\mathbf{d}_{vA}|} = \mathbf{R}_z(\theta_z)\mathbf{R}_y(\theta_y)\,\mathbf{R}_x^{-1}(\phi_{x1})\mathbf{R}_y^{-1}(\phi_y)\mathbf{R}_z^{-1}(\phi_z)\begin{bmatrix}1\\0\\0\end{bmatrix}\\ \mathbf{d}_{uB} &= \frac{\mathbf{d}_{vB}}{|\mathbf{d}_{vB}|} = \mathbf{R}_z(\theta_z)\mathbf{R}_y(\theta_y)\,\mathbf{R}_x^{-1}(\phi_{x2})\mathbf{R}_y^{-1}(\phi_y)\mathbf{R}_z^{-1}(\phi_z)\begin{bmatrix}1\\0\\0\end{bmatrix}\end{aligned} \tag{91}$$

In Equations (91) the known quantities are the rotation angles of the perspective measurement assembly ϕ_{x1} and ϕ_{x2} and the direction vectors $\mathbf{d}_{uA}$ and $\mathbf{d}_{uB}$ (which are known from use of Equation (90) as a result of the two individual alignment calibrations). The unknowns are the four alignment angles θ_z, θ_y, ϕ_z, and ϕ_y. Since the length of both direction vectors is fixed at unity, there are four independent equations in four unknowns.

Equations (91) can be rewritten as:

$$\begin{aligned}\mathbf{d}_{uA} &= \mathbf{Q}\,\mathbf{R}_x^{-1}(\phi_{x1})\,\mathbf{s} \\ \mathbf{d}_{uB} &= \mathbf{Q}\,\mathbf{R}_x^{-1}(\phi_{x2})\,\mathbf{s}\end{aligned} \tag{92}$$

where matrix $\mathbf{Q}$ is a function of θ_z and θ_y and where vector $\mathbf{s}$ is a function of ϕ_z and ϕ_y. The first equation can be solved for $\mathbf{s}$ to give:

$$\mathbf{s} = \mathbf{R}_x(\phi_{x1})\,\mathbf{Q}^{-1}\mathbf{d}_{u1} \tag{93}$$

and this can be substituted in the second equation to give:

$$\mathbf{d}_{uA} = \mathbf{Q}\,\mathbf{R}_x^{-1}(\phi_{x2})\mathbf{R}_x(\phi_{x1})\,\mathbf{Q}^{-1}\mathbf{d}_{uB} \tag{94}$$

Equation (94) represents two non-linear equations in two unknowns. It can be solved for θ_z and θ_y by an iterative numerical procedure, such as Newton's method. In fact, (94) can be solved by a non-linear optimization process similar to that described above in the discussion of optical calibration.

Once these two angles are known, they can be substituted into Equation (93) to solve for ϕ_z and ϕ_y. This latter solution is straightforward. The vector $\mathbf{s}$ can be written explicitly as:

$$\mathbf{s} = \begin{bmatrix} \cos(\phi_y)\cos(\phi_z) \\ \cos(\phi_y)\sin(\phi_z) \\ -\sin(\phi_y) \end{bmatrix} \tag{95}$$

so that the z component of $\mathbf{s}$ will give ϕ_y easily.

I note for completeness that one can also calibrate such a system with a combination of mechanical and optical techniques. One can use the test rig of Figure 43 to directly measure the angles ϕ_y and ϕ_z that the mechanical rotation axis makes with respect to the translation axis. When one does this, one is also inherently defining the specific orientation of the translation y and z axes, so that then one must set the zero point on protractor 670 to correspond with this specific orientation and also to define a plane which contains the optical axis of the borescope. Once these conditions have been satisfied, one then can use Equation (89) to determine the alignment angles θ_y and θ_z of the translation with respect to the visual coordinate system using standard alignment calibration data, in the same manner as was discussed above.

8. Additional Applications and Embodiments

The improved system I have described is also applicable to any single camera, linear motion embodiment of the perspective measurement system, if the camera is given a similar freedom to rotate about an axis which is not aligned with the linear motion. Figures 40, 46, and 47 apply just as well to this case as to the borescope/BPA embodiment discussed in detail. The same measurements, the same equations, and the same expanded alignment calibration as I have disclosed can be used to perform an accurate perspective measurement with such an embodiment.

Although the improved system has been described with reference to particular embodiments, it will be understood by those skilled in the art that it is capable of a variety of alternative embodiments.

For example, one may use a pair of spherical bodies attached to and arranged so as to surround the borescope and disposed with some separation along its length, instead of the cylindrical calibration sleeve of my preferred embodiments. This structure would allow the borescope the required two degrees of motional freedom (when

located in the V groove, but not clamped in position) and yet would provide the required orientation control when used in conjunction with the BPA.

It has been mentioned that there are any number of alternative groove shapes that can be used instead of my preferred V groove for the BPA reference surface. One could also use two separate short V grooves to locate the calibration sleeve, unlike the single long V groove of my preferred embodiments. In this case, the two V grooves would have to be accurately aligned with respect to each other, but this construction could save weight.

Another alternative would be to use a cylindrical reference surface on the BPA and a V groove mounted on the borescope. This would work just as well as the preferred embodiments in terms of the accuracy of the measurement. The disadvantage is that the centerline of the borescope would move with respect to the BPA as the borescope was rotated, thus making it more difficult to perform the measurement through a small inspection port as shown in Figure 4.

The reference surface on the borescope does not have to be mounted over the lens tube, as it is in my preferred embodiments. Depending on the detailed construction of the individual borescope and on the need for a translational degree of freedom in the application, it is possible to provide the reference surface somewhere on the body of the borescope. The advantage is that there is then less of the length of the borescope lens tube dedicated to the support of the borescope, and thus more of the length is useable for reaching deep into an enclosure.

It is also possible to provide systems which have only the rotational degree of freedom, for those applications in which the depth of the object of interest is fixed. One simple example is that a specific region of the lens tube envelope could be marked as the region to be clamped into the BPA. If the borescope is always clamped at this same position, then there will be no change in alignment because of curvature of the lens tube envelope. This simple system is still subject to lack of repeatability in the alignment because of non-circularity of the lens tube, but it may be adequate for certain applications.

The system of using complementary reference surfaces to provide a repeatable relative alignment between a borescope and a borescope positioner could also be used with other, less complete, measurement systems which were known prior to my perspective measurement system to allow more flexibility in aligning the view to objects of interest.

Conclusion, Ramifications, and Scope

Accordingly, the reader will see that the dimensional measurement system of this invention has many advantages over the prior art. My system provides more accurate measurements than hitherto available, because I show how to arrange the measurement to minimize the inherent random errors, and also because I show how to determine and take into account the actual geometry of and any systematic errors in the hardware. My system provides measurements at lower cost than previously available because I correctly teach how to add the measurement capability to current, widely available, visual inspection hardware. In addition, my system provides a more flexible measurement technique than previously known, in that I teach how to make measurements that are simply impossible with the prior art. Using my invention, it is possible to build special purpose measurement systems to meet any number of specific measurement requirements that are currently not being adequately addressed.

Although the invention has been described with reference to particular embodiments, it will be understood by those skilled in the art that the invention is capable of a variety of alternative embodiments within the spirit and scope of the appended claims.

Claims:

1. A method of perspective measurement of the three-dimensional size of a remote object using a camera having a field of view, said camera being translated along a substantially straight line from a first viewing position to a second viewing position, characterized by the use of a fully three-dimensional least squares estimation procedure to determine the measurement result.

2. A method as claimed in claim 1, wherein said camera also has an internal coordinate system, and wherein the orientation of said camera internal coordinate system with respect to said substantially straight line is determined in a calibration process and wherein said orientation is taken into account in the measurement result, and wherein, optionally, errors in the motion of the camera are also determined in a calibration process and these errors are then also taken into account in the measurement result.

3. A method as claimed in either of claim 1 or claim 2, wherein the first and second viewing positions are selected so that a single point on the object is viewed at an apparent angular position near one edge of the field of view at the first viewing position, and at substantially the same apparent angle on the other side of the field of view at the second viewing position, thereby minimizing the random error in the measurement.

4. A method of determining a set of three - dimensional coordinates for at least one point on an inaccessible object, thereby determining a location vector for each of said at least one point, characterized by the steps of:
(a) providing one or more cameras, each of which has an internal coordinate system and an effective focal length, and providing motion means for moving said one or more cameras with respect to the inaccessible object, and further providing a plurality of predetermined relative camera positions for each of said cameras, wherein each of said cameras has a spatial orientation at each of said relative positions, and wherein said relative positions and said spatial orientations are determined in an external coordinate system;
(b) acquiring a set of first images of said at least one point with one of said one or more cameras located at a first viewing position, wherein said first viewing position also corresponds to one of said predetermined relative camera positions, said camera having a first spatial orientation at said first viewing position, thereby defining a first measurement coordinate system which is coincident with the internal coordinate system of said camera at said first viewing position;
(c) measuring the coordinates of each of said first images of said at least one point in said first measurement coordinate system;
(d) acquiring a set of second images of said at least one point with one of said one or more cameras located at a second viewing position, wherein said second camera viewing position also corresponds to one of said predetermined relative camera positions, said camera having a second spatial orientation at said second viewing position, thereby defining a second measurement coordinate system which is coincident with the internal coordinate system of said camera at said second viewing position;

(e) measuring the coordinates of each of said second images of said at least one point in said second measurement coordinate system;

(f) correcting the measured coordinates of each of said first images of said at least one point to adjust for any distortion of the camera located at the first viewing position, and correcting the measured coordinates of each of said second images of said at least one point to adjust for any distortion of the camera located at the second viewing position, thereby producing sets of first and second final point image coordinates for said first and second viewing positions in said first and second measurement coordinate systems;

(g) multiplying the first final point image coordinates by the mathematical inverse of the effective focal length of the camera located at the first viewing position and multiplying the second final point image coordinates by the mathematical inverse of the effective focal length of the camera located at the second viewing position, to determine the mathematical tangents of the angles at which each of said at least one point is viewed in said first and second measurement coordinate systems; and

(h) forming least squares estimates of the three dimensional coordinates for each of said at least one point in a third measurement coordinate system using said mathematical tangents of the viewing angles for each of said at least one point in said first and second measurement coordinate systems and the relationships between said first and second camera viewing positions and said first and second camera spatial orientations determined in said external coordinate system, thereby forming a least squares estimate of the location vector for each of said at least one point in said third measurement coordinate system.

5. A method as claimed in claim 4, wherein the third measurement coordinate system is the same as the first measurement coordinate system, and/or the predetermined relative camera positions all lie along a substantially straight line or along a substantially circular arc.

6. A method as claimed in claim 5, wherein the spatial orientation of the camera at the first viewing is substantially the same as the spatial orientation of the camera at the second viewing position, or wherein at least one camera is free to rotate about a single axis perpendicular to said straight line or said circular arc.

7. A method as claimed in claim 5, wherein said relative camera positions lie along said circular arc, said circular arc having a center of curvature, and wherein each of said one or more cameras has an optical axis, and wherein the orientation of each of said one or more cameras is coupled to its position along the arc so that said optical axis is always substantially aligned with said center of curvature of the arc or wherein the orientation of each of said one or more cameras is such that said optical axis is aligned substantially perpendicular to the plane containing the arc.

8. The method of claim 4 for determining the three-dimensional distances between the points of each pair of any set of pairs of points in a plurality of points on an inaccessible object, characterized by the further steps of:

(i) performing steps (a) through (h) of claim 4 for said plurality of points;

(j) determining a difference vector between the location vectors of a first pair of said set of pairs of points by subtracting the location vector of a first point of said pair from the location vector of the second point of said pair;

(k) determining the length of the difference vector by calculating the square root of the sum of the squares of the components of the difference vector; and

(l) repeating steps (j) and (k) as necessary to determine the distances between the points of all remaining pairs in said set of pairs of points.

9. The method of claim 4 for determining the three-dimensional distances between a pair of points on an object, characterized by the further steps of:

(i) performing steps (a) through (h) of claim 4 for a first point of said pair of points, wherein said first and second viewing positions define respectively first and second camera location vectors in said external coordinate system, and identifying said third measurement coordinate system as a first temporary coordinate system, wherein said first temporary coordinate system has an origin and wherein said origin has a vector location in said external coordinate system;

(j) calculating the vector location of said first point in said external coordinate system by adjusting the vector location of said first point in said first temporary coordinate system according to the first and second camera spatial orientations used in step (i);

(k) calculating the vector location of the origin of the first temporary coordinate system by forming the average of said first and second camera location vectors;

(l) performing steps (b) through (h) of claim 4 for a second point of said pair of points, wherein at least one of said first and second viewing positions are different from either of the first and second viewing positions used in step (i), and wherein said first and second viewing positions now define respectively third and fourth camera location vectors in said external coordinate system, and identifying said third measurement coordinate system as a second temporary coordinate system, wherein said second temporary coordinate system has an origin and wherein said origin has a vector location in said external coordinate system;

(m) calculating the vector location of said second point in said external coordinate system by adjusting the vector location of said second point in said second temporary coordinate system according to the first and second camera spatial orientations used in step (l);

(n) calculating the vector location of the origin of the second temporary coordinate system by forming the average of said third and fourth camera location vectors;

(o) calculating a vector from the origin of the second temporary coordinate system to the origin of the first temporary coordinate system by subtracting the vector location of the origin of the second temporary coordinate system from the vector location of the origin of the first temporary coordinate system;

(p) calculating the vector from the second point of said pair of points to the first point of said pair of points with the equation

$$\mathbf{r} = \mathbf{d}_{AB} + \mathbf{r}_{AG} - \mathbf{r}_{BG}$$

wherein $\mathbf{d}_{AB}$ is the vector from the origin of the second temporary coordinate system to the origin of the first temporary coordinate system, $\mathbf{r}_{AG}$ is the vector location of said first point in said external coordinate system, and $\mathbf{r}_{BG}$ is the vector location of said second point in said external coordinate system; and

(q) calculating the distance between said pair of points by calculating the length of the vector $\mathbf{r}$.

10. In an apparatus for measuring three - dimensional distances between selected points on an inaccessible object, wherein the apparatus includes a rigid borescope which is fastened to a linear motion means, said linear motion means having a range of travel and which also constrains the borescope to move along a substantially straight line, said apparatus further comprising a driving means which controls the position of the linear motion means within its range of travel and also a position measurement means for indicating the position of said linear motion means, the improvement characterized by the use of a linear motion means selected from the group consisting of crossed roller slides and ball slides and air bearing slides and dovetail slides, wherein the linear motion means is preferably a linear translation stage, the driving means is preferably an actuator, and the position measurement means is preferably a linear position transducer attached to said translation stage.

11. In an apparatus for measuring three - dimensional distances between selected points on an inaccessible object, wherein the apparatus includes a rigid borescope which is fastened to a linear motion means, said linear motion means having a range of travel and which also constrains the borescope to move along a substantially straight line, said apparatus further comprising a driving means which controls the position of the linear motion means within its range of travel and also a position measurement means for indicating the position of said linear motion means, the improvement characterized by the use of a lead screw and nut as a driving means and, optionally, wherein both the driving means and the position measurement means are embodied in a micrometer.

12. An apparatus as claimed in either of claim 10 or claim 11 wherein said borescope has a field of view, and wherein said borescope includes a video imaging means, and wherein said video imaging means is comprised of a video sensor optically coupled to said borescope, and wherein said video sensor has different spatial resolutions along its two sensing axes, further wherein said video sensor is rotationally oriented with respect to said borescope such that its higher spatial resolution axis is aligned substantially parallel to the projection of the linear motion of the borescope as observed in the field of view, thereby obtaining the highest precision in the distance measurement.

13. An electronic measurement borescope apparatus for measuring three - dimensional distances between selected points on an inaccessible object, characterized by:

(a) a video camera, including an imaging lens and a solid state imager, for producing video images of the object, and a video monitor, for displaying said video images;

(b) a linear translation means, for moving the video camera with a substantially constant orientation along a substantially straight line, said linear translation means and camera being disposed at the distal end of a rigid probe, and said linear motion means also having a range of travel;

(c) an actuating means, for moving the linear translation means to any position within its range of travel;

(d) a position measurement means, for determining the position of the linear translation means within said range of travel, whereby the position of the video camera is also determined, said position measurement means also producing position measurement data, said position measurement means also having a first data transfer means for supplying the camera position data to a computing means;

(e) a video cursor means, for displaying variable position cursors on said video image, said video cursor means having a second data transfer means for supplying the spatial positions of said variable position cursors to the computing means; and

(f) said computing means having a user interface, said user interface being in communication with said video cursor means and said second data transfer means such that a user can manipulate said video cursor means until said variable position cursors are aligned with the images of said selected points on said inaccessible object, and further such that said spatial positions of said variable position cursors are supplied to the computing means at user command, and further such that said computing means receives the camera position data through said first data transfer means, and further such that said computing means calculates and displays the three - dimensional distances between the selected points on said inaccessible object.

14. An apparatus as claimed in claim 13, wherein the actuating means is a motorized micrometer driving a positioning cable, said cable being looped around a pair of idler pulleys and being attached to the linear translation means or wherein the actuating means is a motorized micrometer located at the distal end of said rigid probe, said motorized micrometer being attached to the linear translation means.

15. An electronic measurement endoscope apparatus for measuring three - dimensional distances between selected points on an inaccessible object, characterized by:
   (a) a video camera, including an imaging lens and a solid state imager, for producing video images of the object, and a video monitor, for displaying said video images;
   (b) a linear translation means, for moving the video camera with a substantially constant orientation along a substantially straight line, said linear translation means also having a range of travel, and said linear translation means and camera being disposed internally into a rigid housing, said rigid housing being disposed at the distal end of a flexible endoscope housing;
   (c) an actuating means, for moving the linear translation means to any position within its range of travel;
   (d) a position measurement means, for determining the position of the linear translation means within said range of travel, whereby the position of the video camera is also determined, said position measurement means also producing position measurement data, said position measurement means also having a first data transfer means for supplying the position measurement data to a computing means;
   (e) a video cursor means, for displaying variable position cursors on said video image, said video cursor means having a second data transfer means for supplying the spatial positions of said variable position cursors to the computing means; and
   (f) said computing means having a user interface, said user interface being in communication with said video cursor means and said second data transfer means such that a user can manipulate said video cursor means until said variable position cursors are aligned with the images of said selected points on said inaccessible object, and further such that said spatial positions of said variable position cursors are supplied to the computing means at user command, and further such that said computing means receives the camera position data through said first data transfer means, and further such that said computing means calculates and displays the three - dimensional distances between the selected points on said inaccessible object.

16. An apparatus as claimed in claim 15, wherein the actuating means is a positioning wire encased in a sheath, which is driven by a motorized micrometer, or wherein the actuating means is a motorized micrometer located at the distal end of the apparatus, said motorized micrometer being attached to the linear translation means.

17. An apparatus as claimed in any one of claims 13 to 16, wherein said video camera has a field of view, and wherein an illumination means for illuminating said field of view is being carried by the linear translation means, such that the illumination of said field of view remains substantially constant as said camera is moved.

18. An apparatus for making measurements of the three-dimensional distances between selected points on an object, said apparatus including a camera, and a support means, whereby said camera can be moved along a substantially straight translational axis from a first viewing position to a second viewing position, and whereby said camera can also be rotated about a rotational axis for alignment with objects of interest prior to a measurement, said rotational axis being at an arbitrary alignment with said translational axis, characterized by:

(a) a means for measurement of an angle of rotation of said camera about said axis of rotation; and

(b) a means for incorporating said measurement of said angle of rotation into said measurements of three-dimensional distances.

19. An apparatus as claimed in claim 18 wherein said means for measurement of an angle of rotation has a first portion which rotates with said camera and also has a second portion which is fixed to said support means, wherein said camera is preferably a substantially side-looking rigid borescope, said borescope having a lens tube envelope and said lens tube envelope having an outer surface, and wherein said support means preferably comprises a borescope positioning assembly and wherein said rotational axis is preferably defined by the engagement of a first reference surface attached to said borescope with a second reference surface attached to said borescope positioning assembly, whereby said first reference surface is preferably a cylinder and said second reference surface is preferably a V groove, and said cylindrical first reference surface is said outer surface of said lens tube envelope or is a calibration sleeve attached to said borescope.

20. An apparatus for making measurements of the three-dimensional distances between selected points on an object, said apparatus including a substantially side-looking rigid borescope which can be moved along a substantially straight translational axis from a first viewing position to a second viewing position, said borescope having a lens tube envelope and said lens tube envelope having an outer surface, and wherein said borescope can also be rotated about a rotational axis for alignment with objects of interest prior to a measurement, characterized by the arrangement of said rotational axis to be accurately aligned with said translational axis.

21. An apparatus as claimed in claim 20 wherein said borescope is preferably moved along said translational axis by a borescope positioning assembly and said rotational axis is preferably defined by the engagement of a first reference surface attached to said borescope with a second reference surface attached to said borescope positioning assembly, whereby said first reference surface is preferably a cylinder and said second reference surface is preferably a V groove, and said cylindrical first reference surface is said outer surface of said lens tube envelope or is a calibration sleeve attached to said borescope.

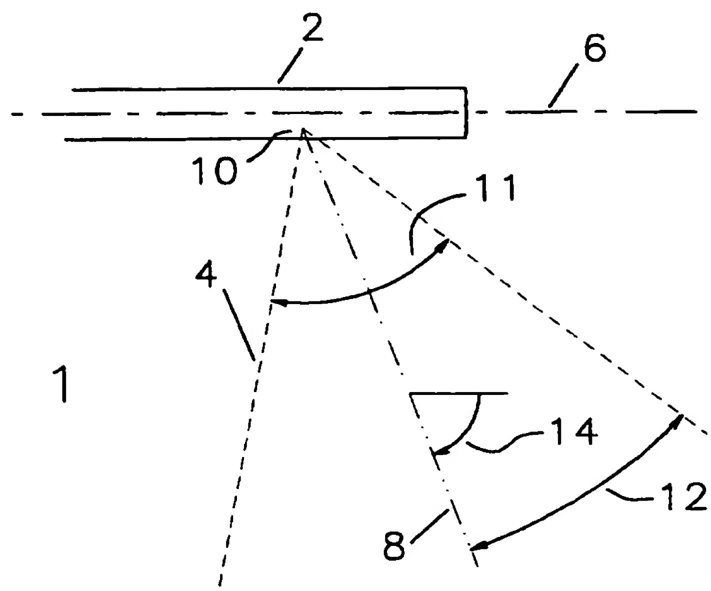
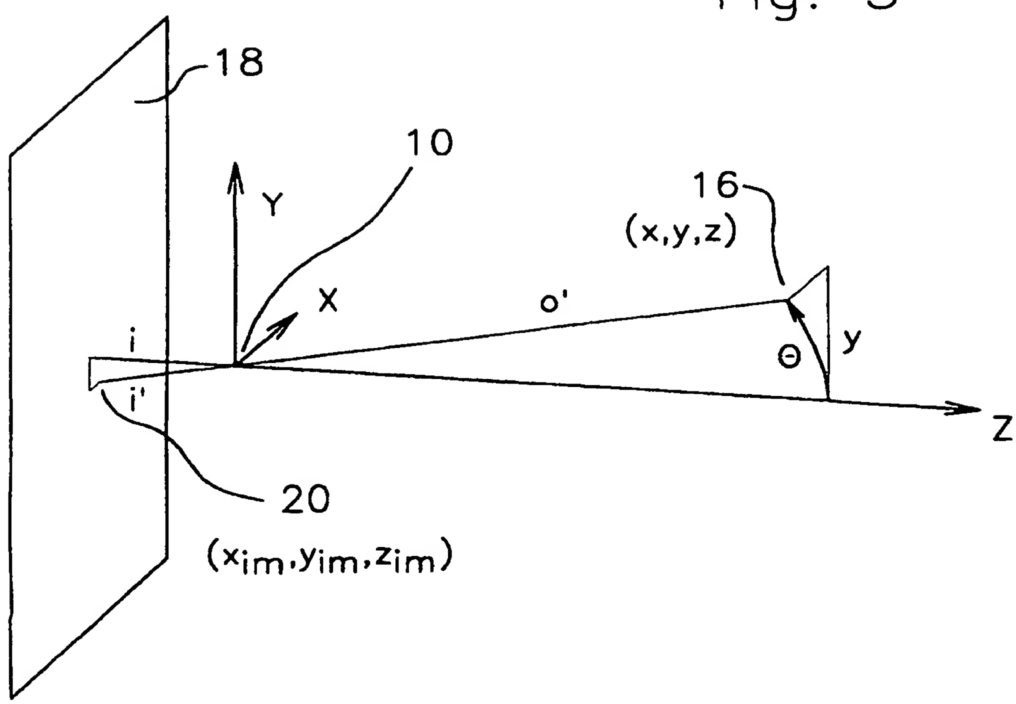
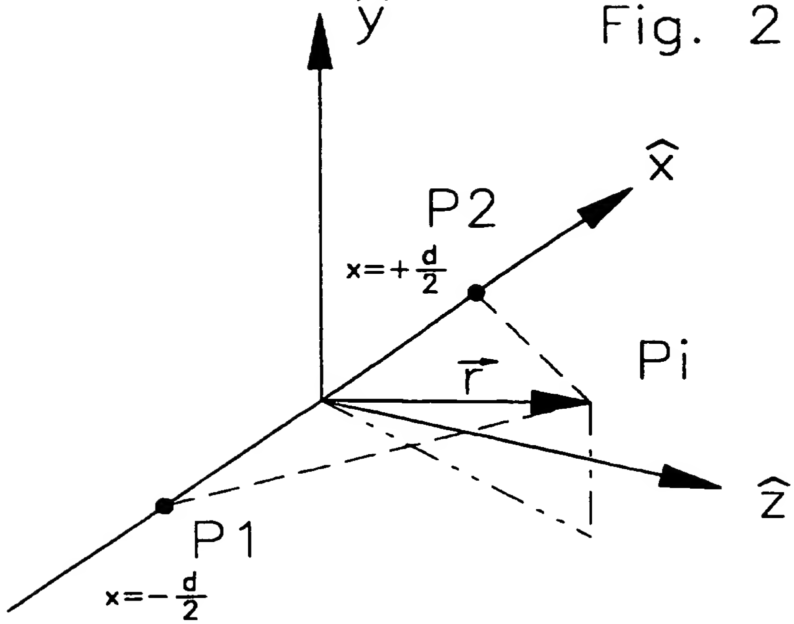


Fig. 1

Fig. 3





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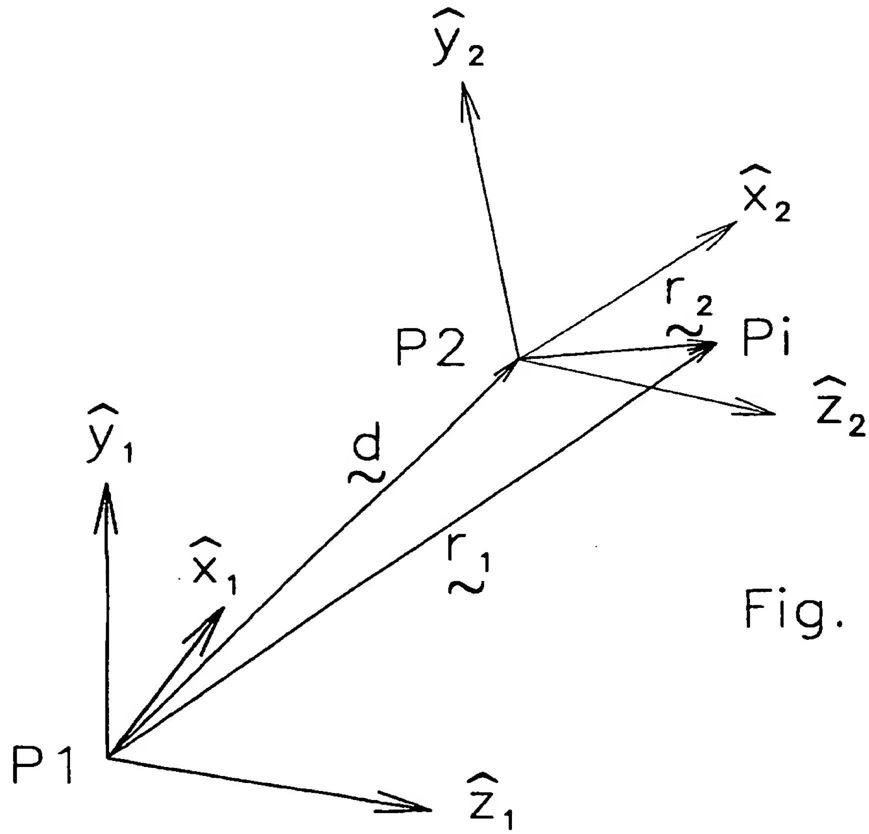
$x=-\frac{d}{2}$

Fig. 2



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P1
$\hat{z}_1$

Fig. 12

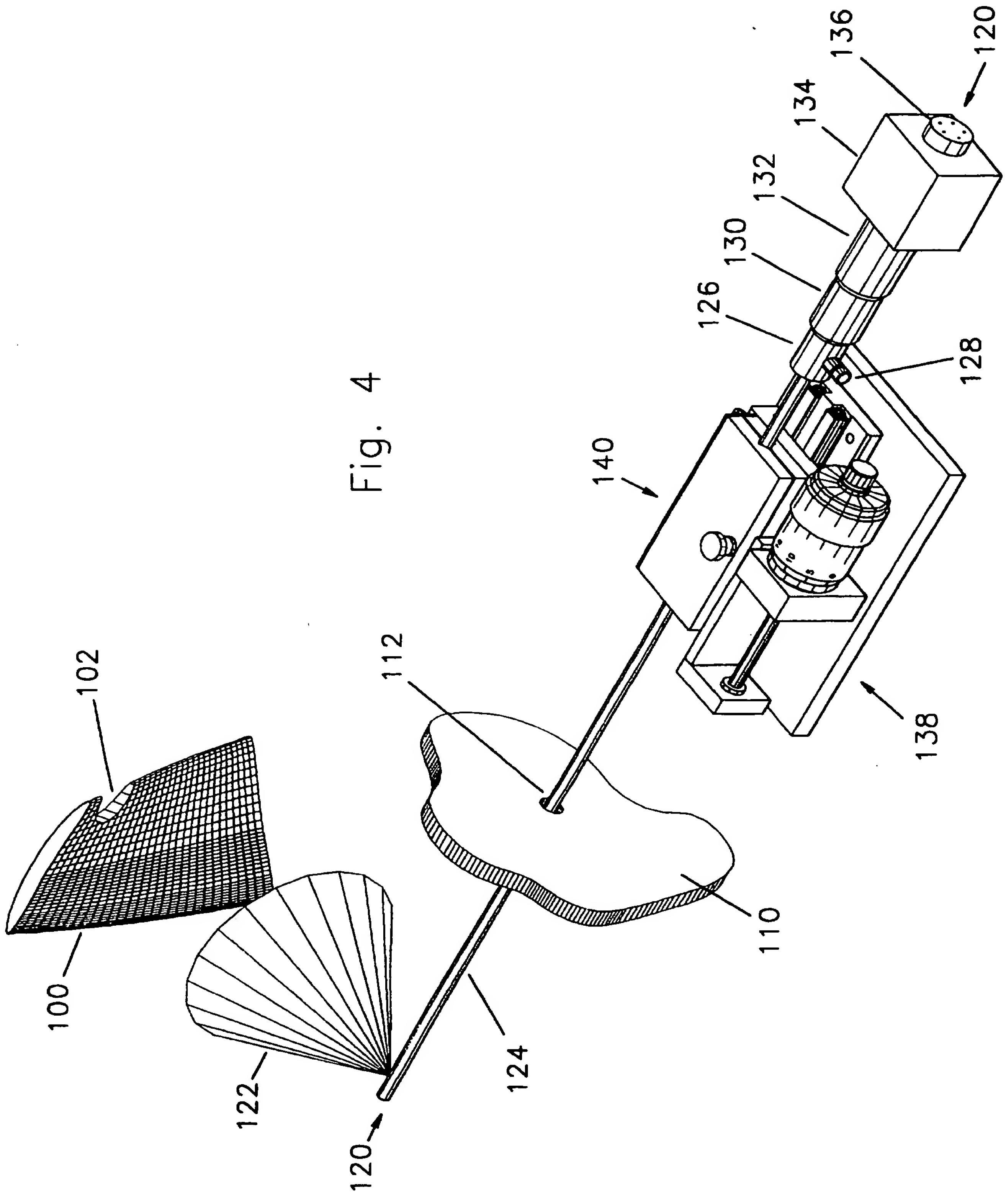
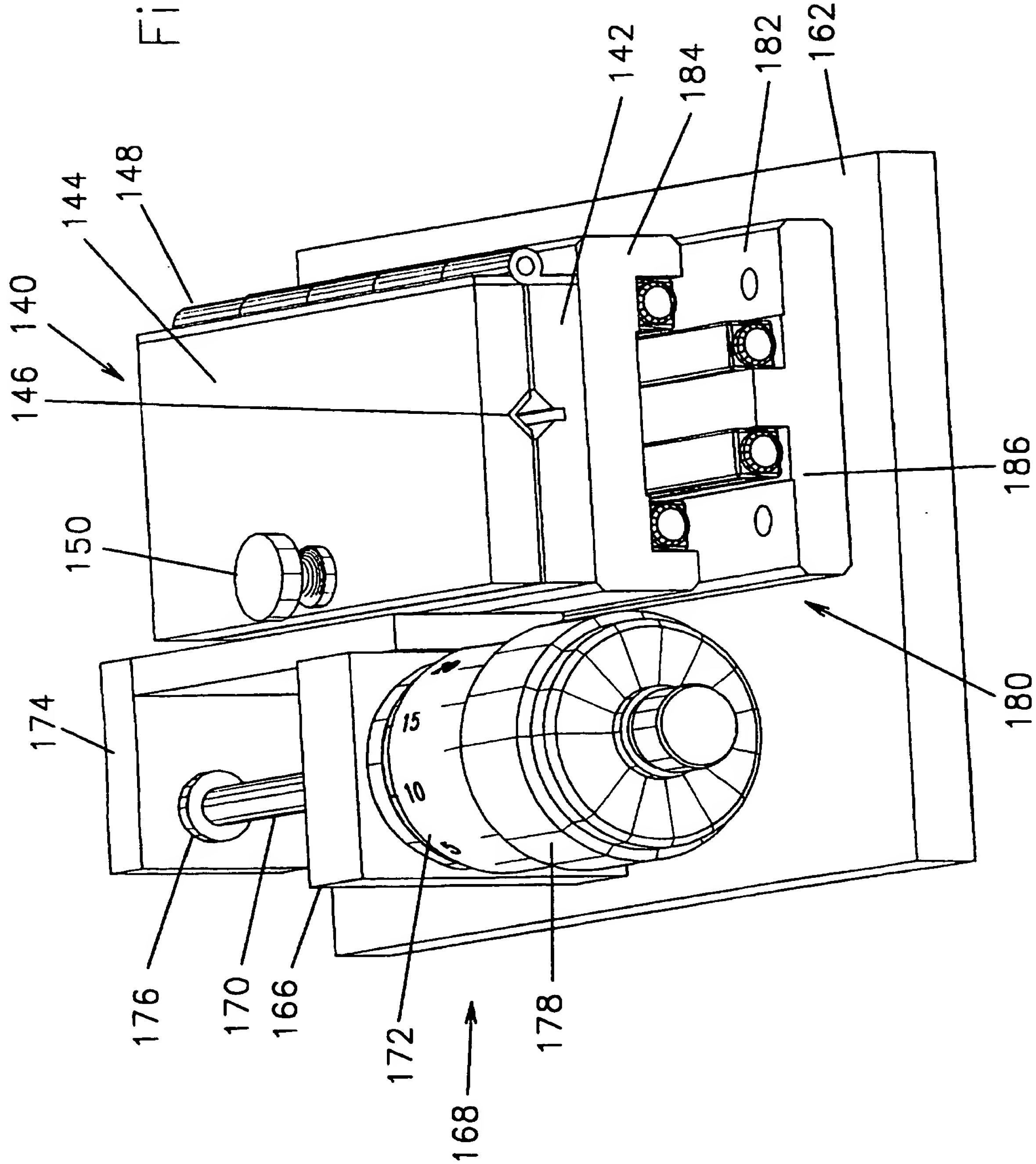


Fig. 4

Fig. 5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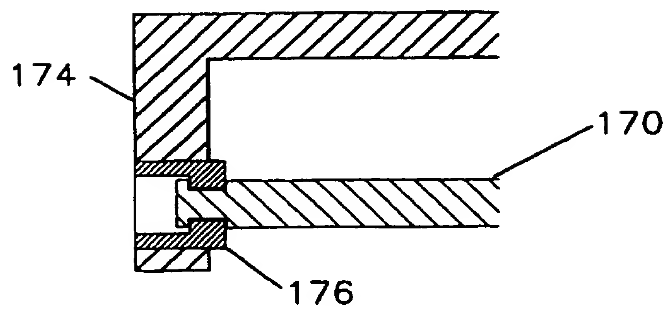
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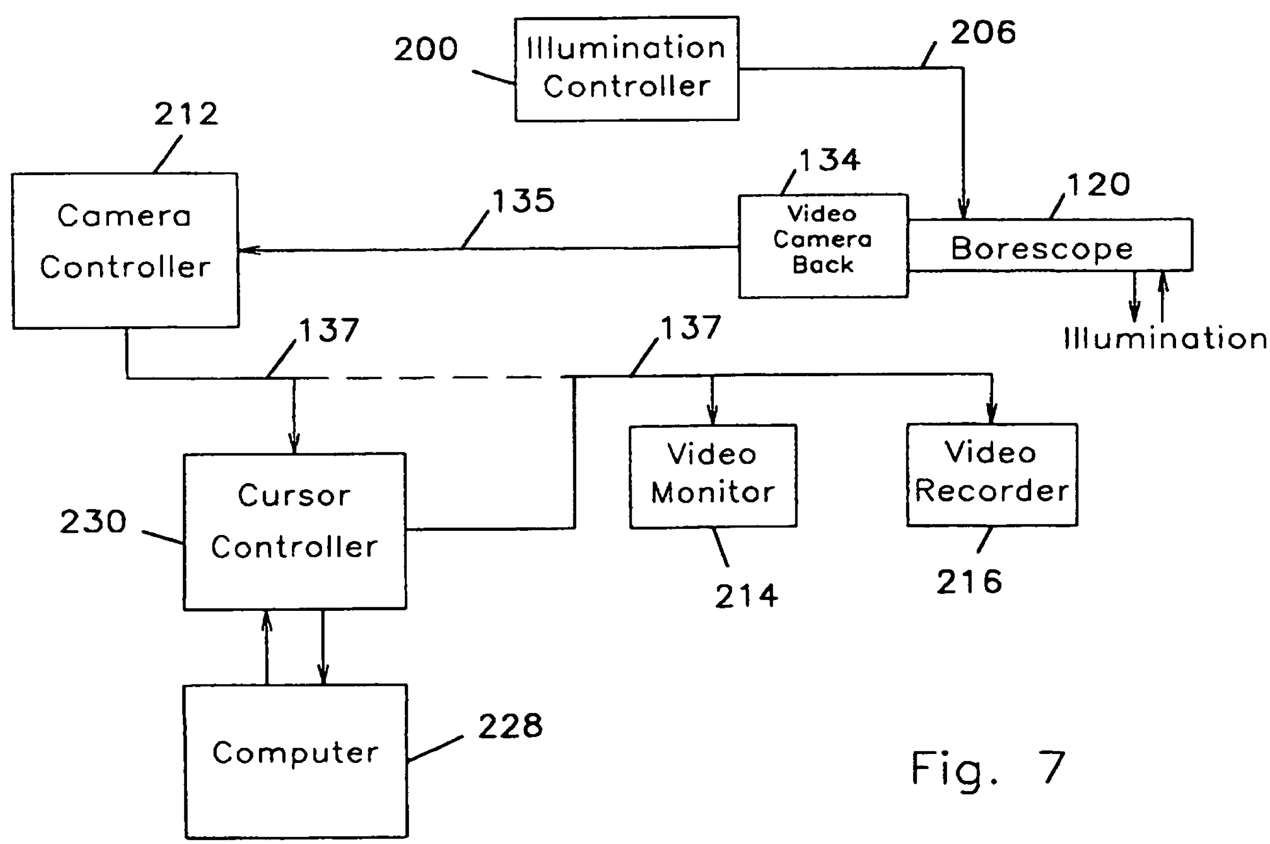
Fig. 6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Illumination Controller
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212
Camera Controller
134
Video Camera Back
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Borescope
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Illumination
137
137
Cursor Controller
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Video Monitor
Video Recorder
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216
Computer
228

Fig. 7

Fig. 8

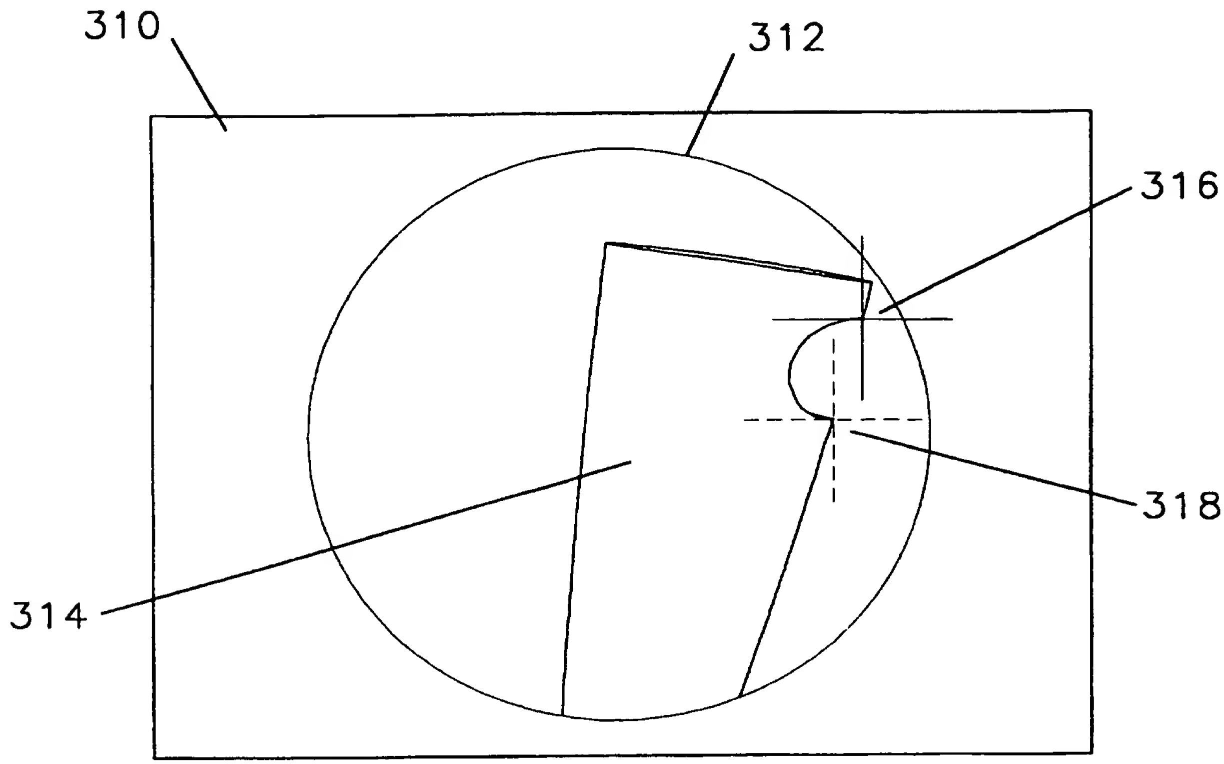


Fig. 9

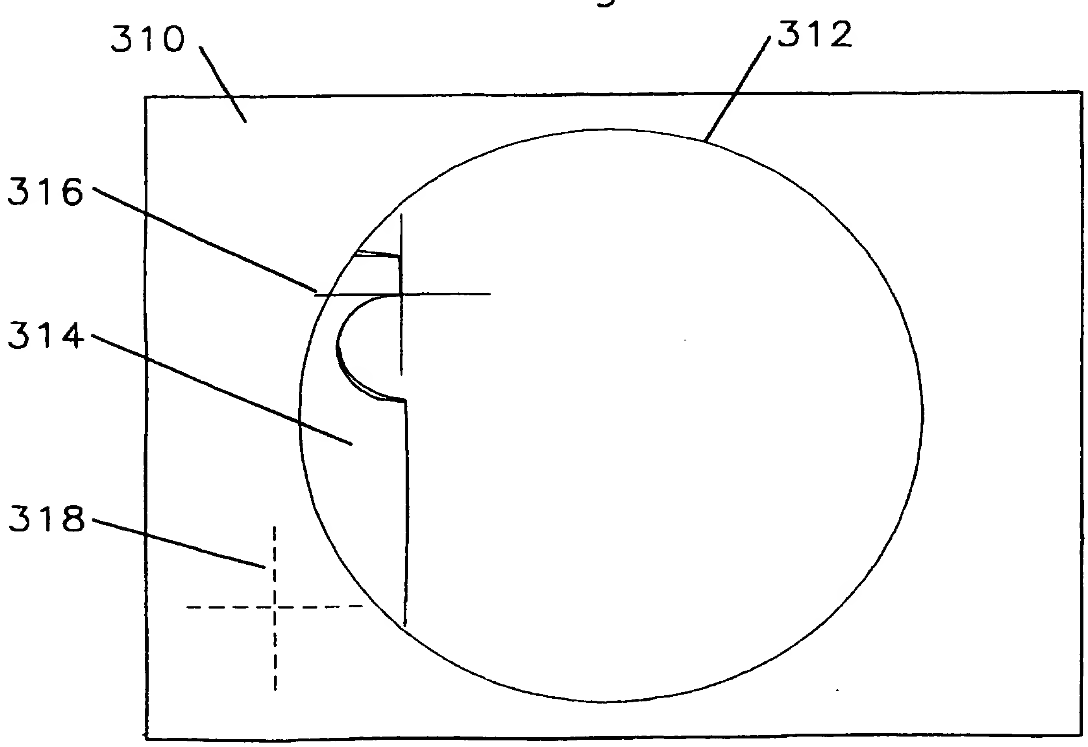


Fig. 10A

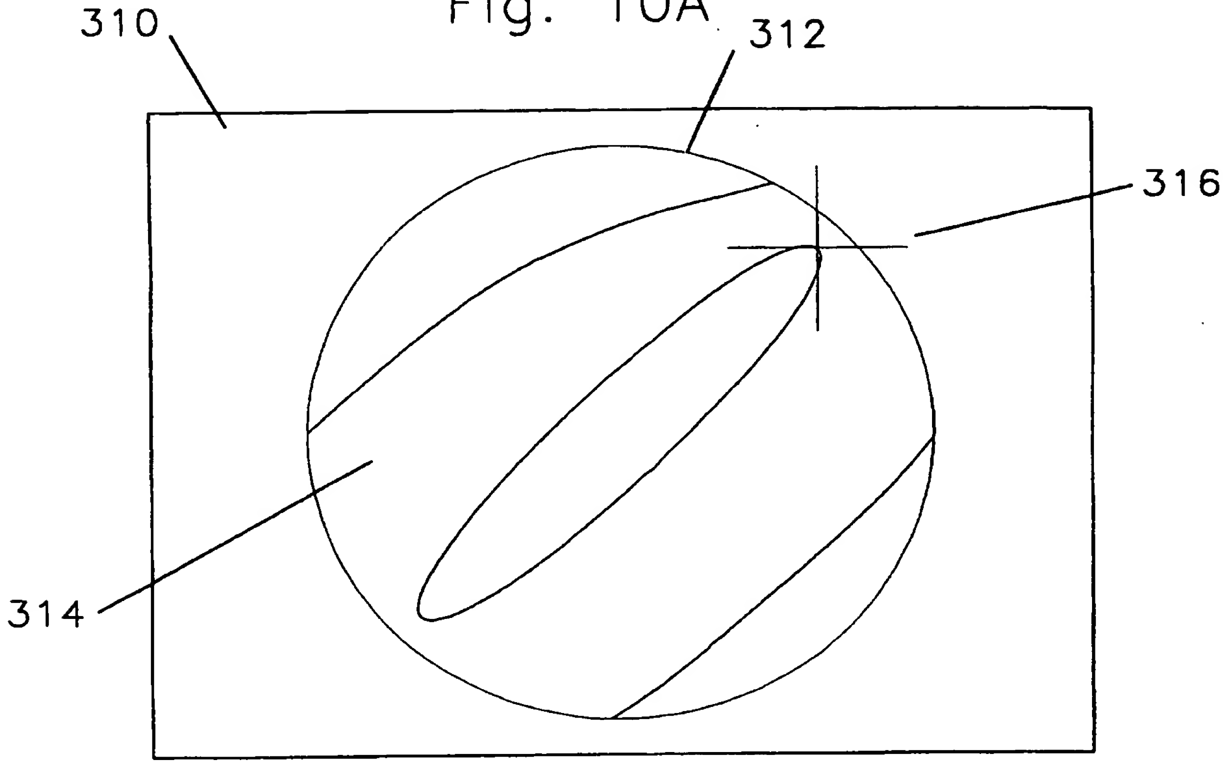


Fig. 10B

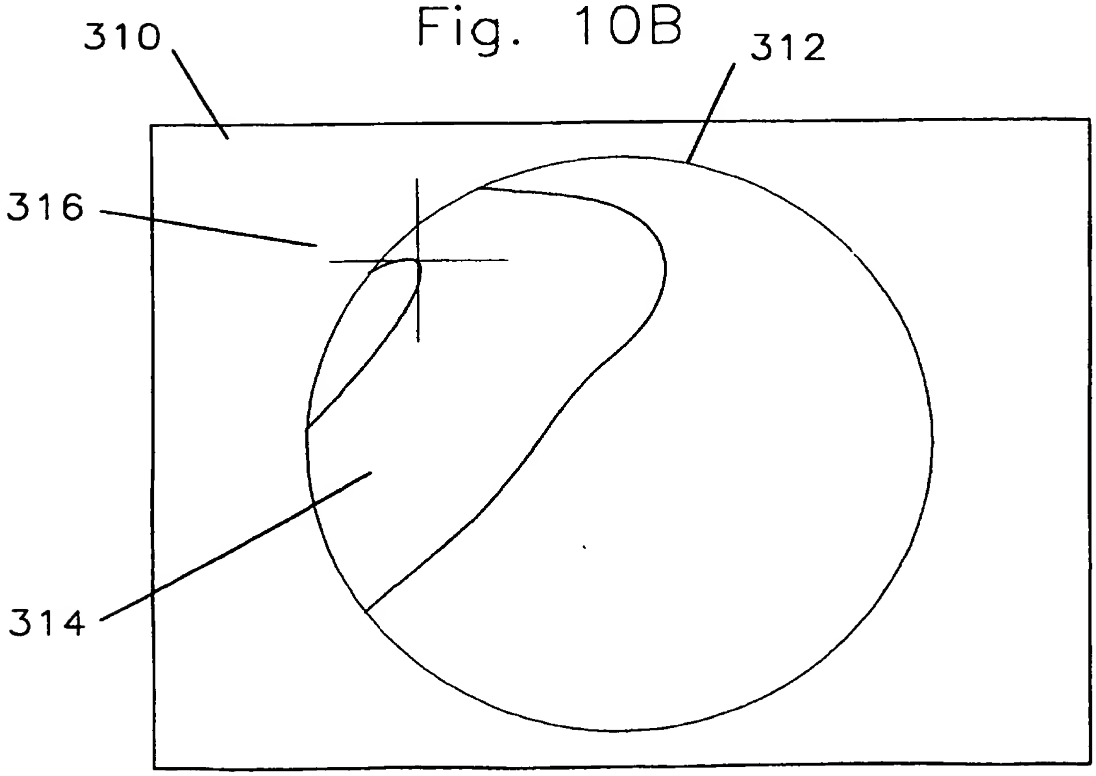


Fig. 11A

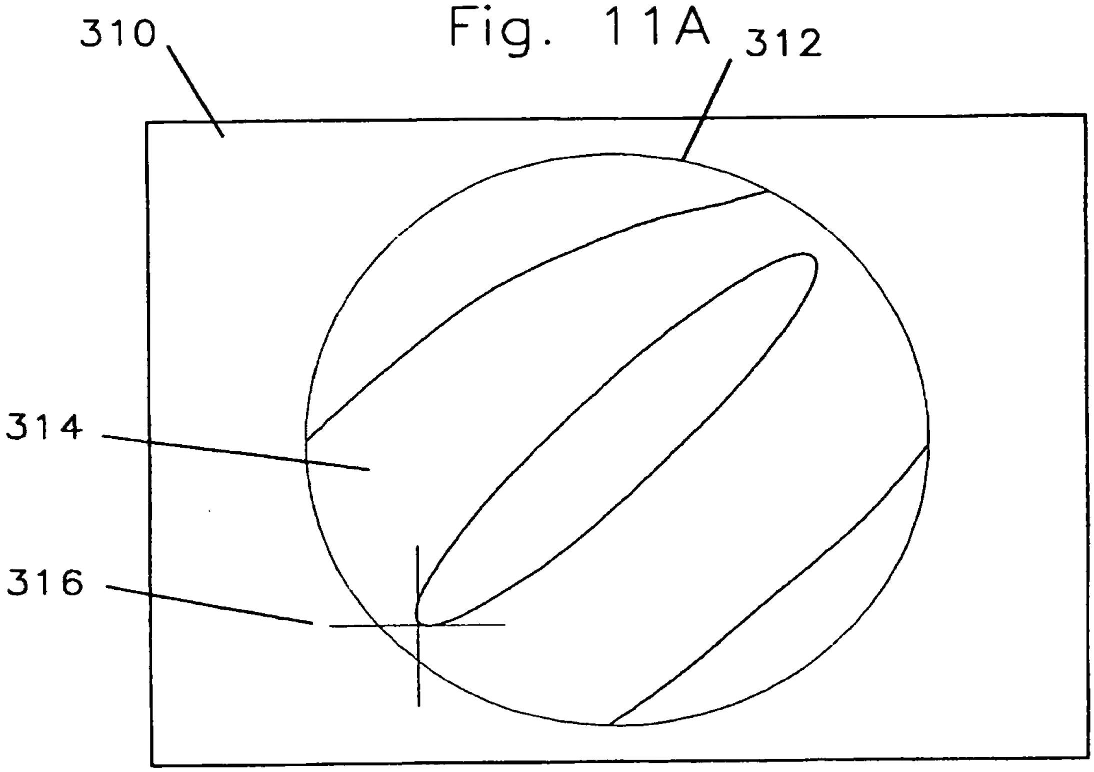


Fig. 11B

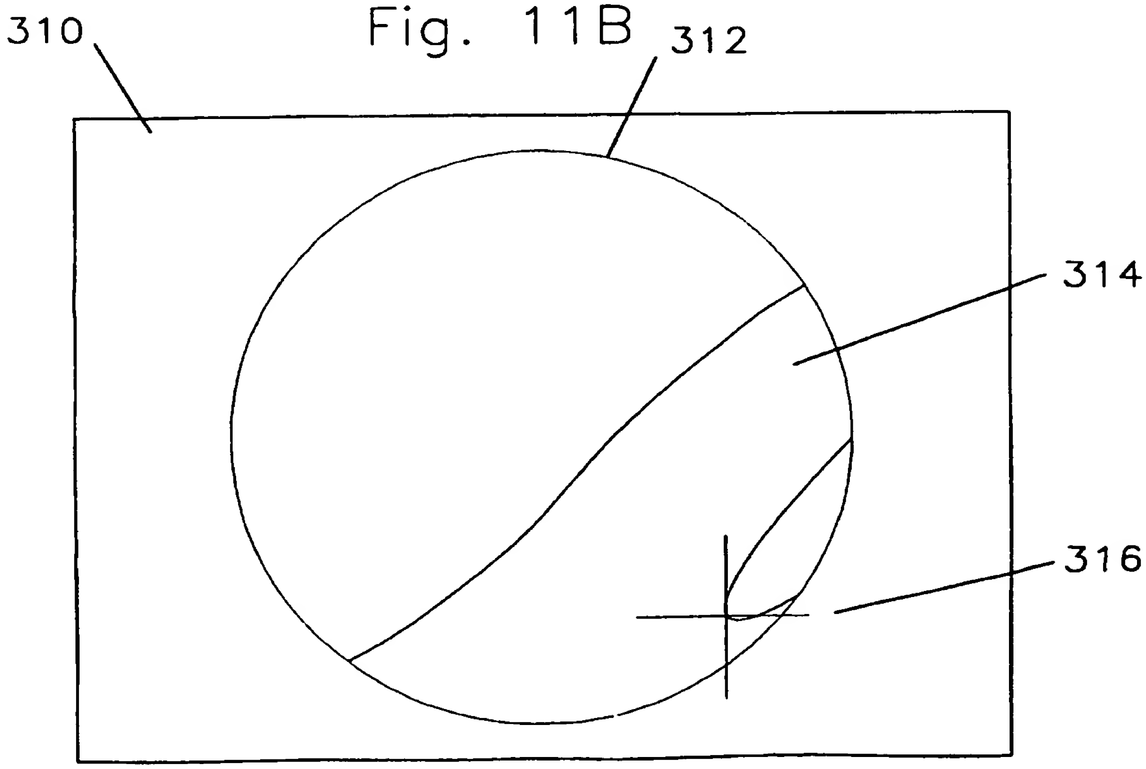
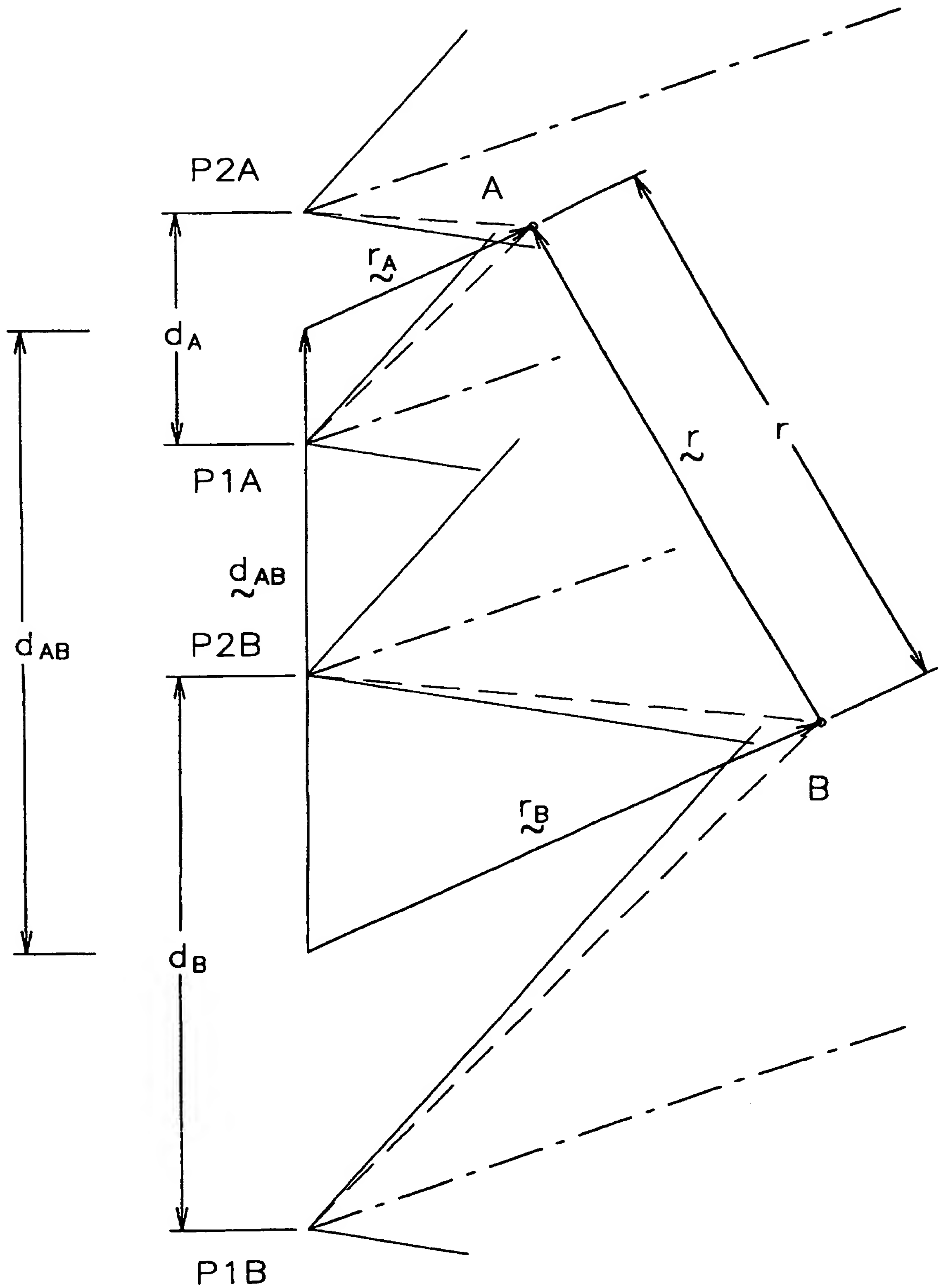


Fig. 13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d_A
P1A
$\underset{\sim}{r}$
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d_{AB}
P2B
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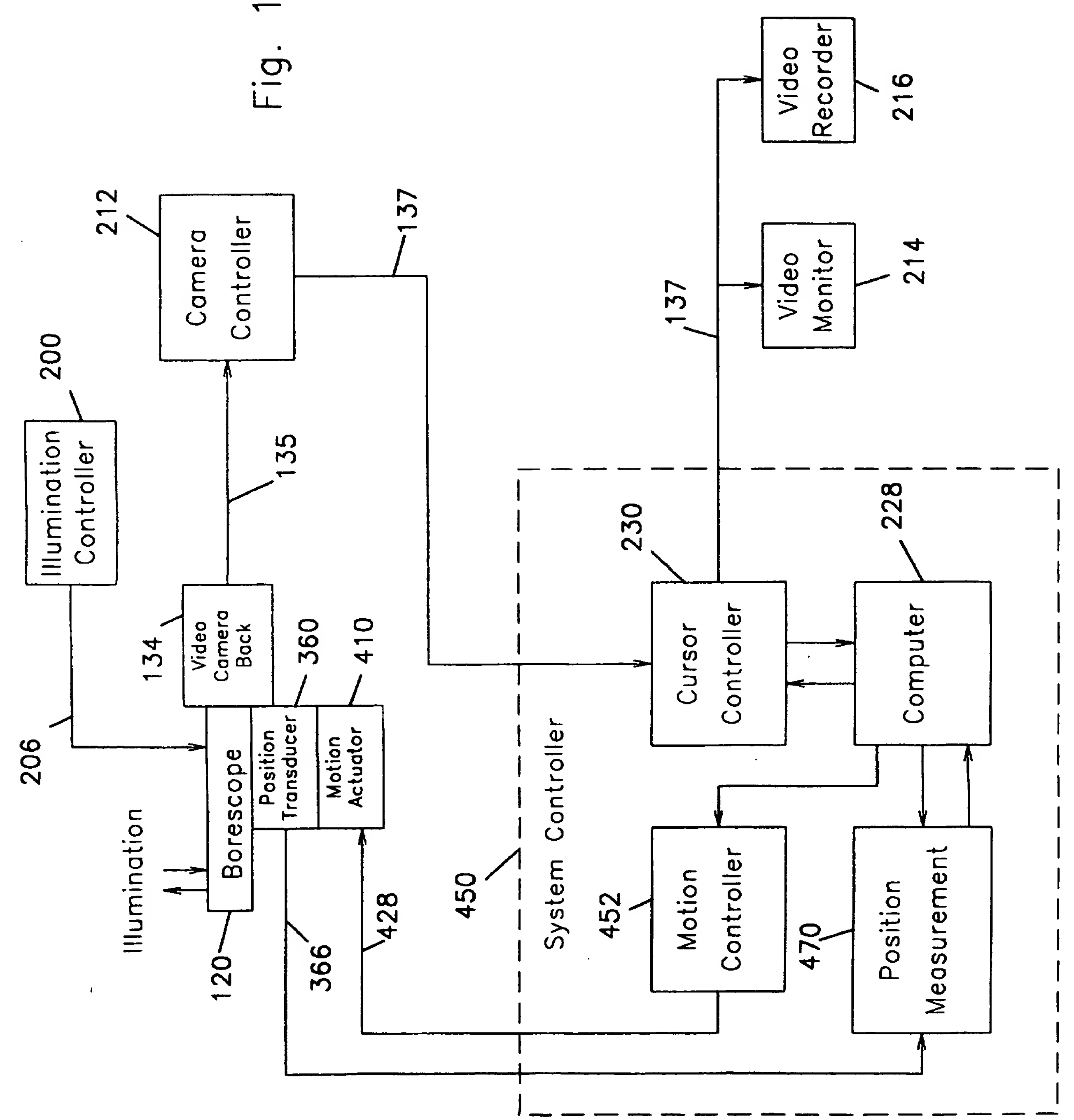
P1B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Video Monitor
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Borescope
Position Transducer
Motion Actuator
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Cursor Controller
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Computer
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Motion Controller
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Position Measurement

Fig. 14

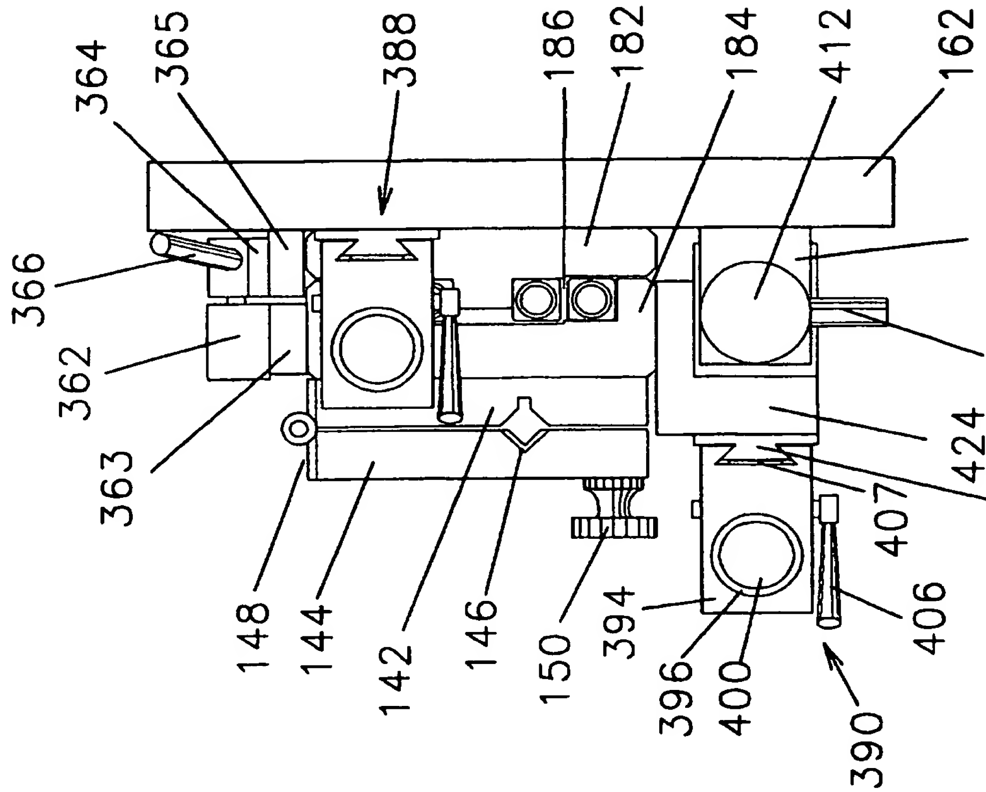
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Fig. 17

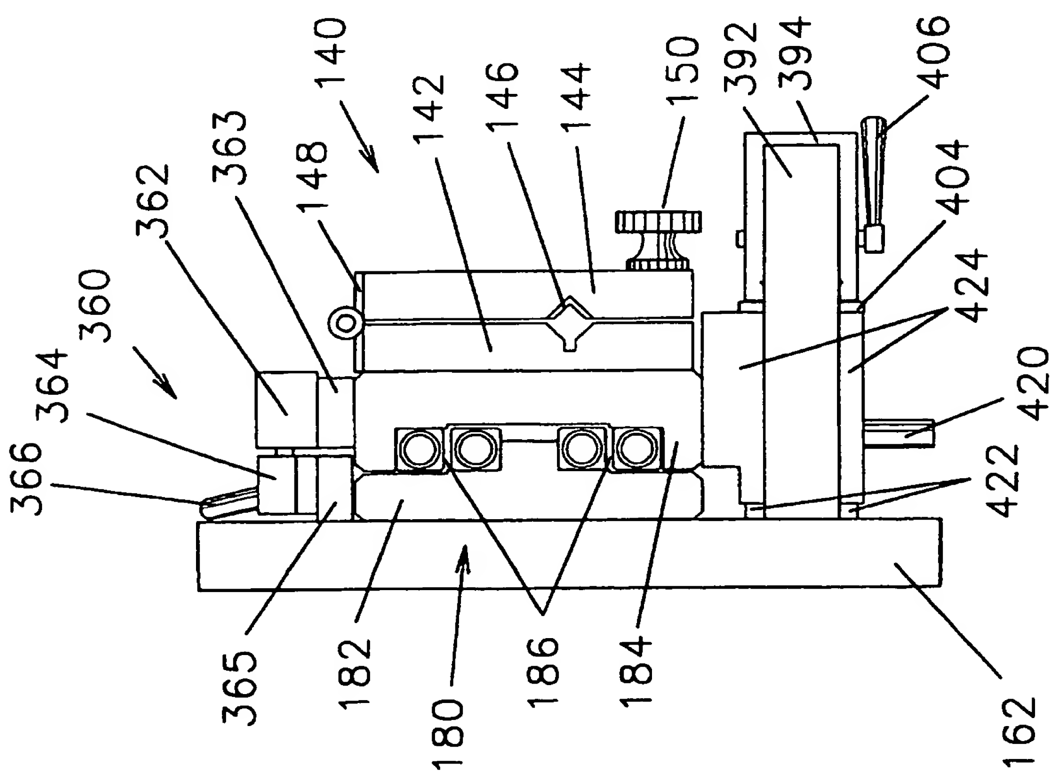
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Fig. 15

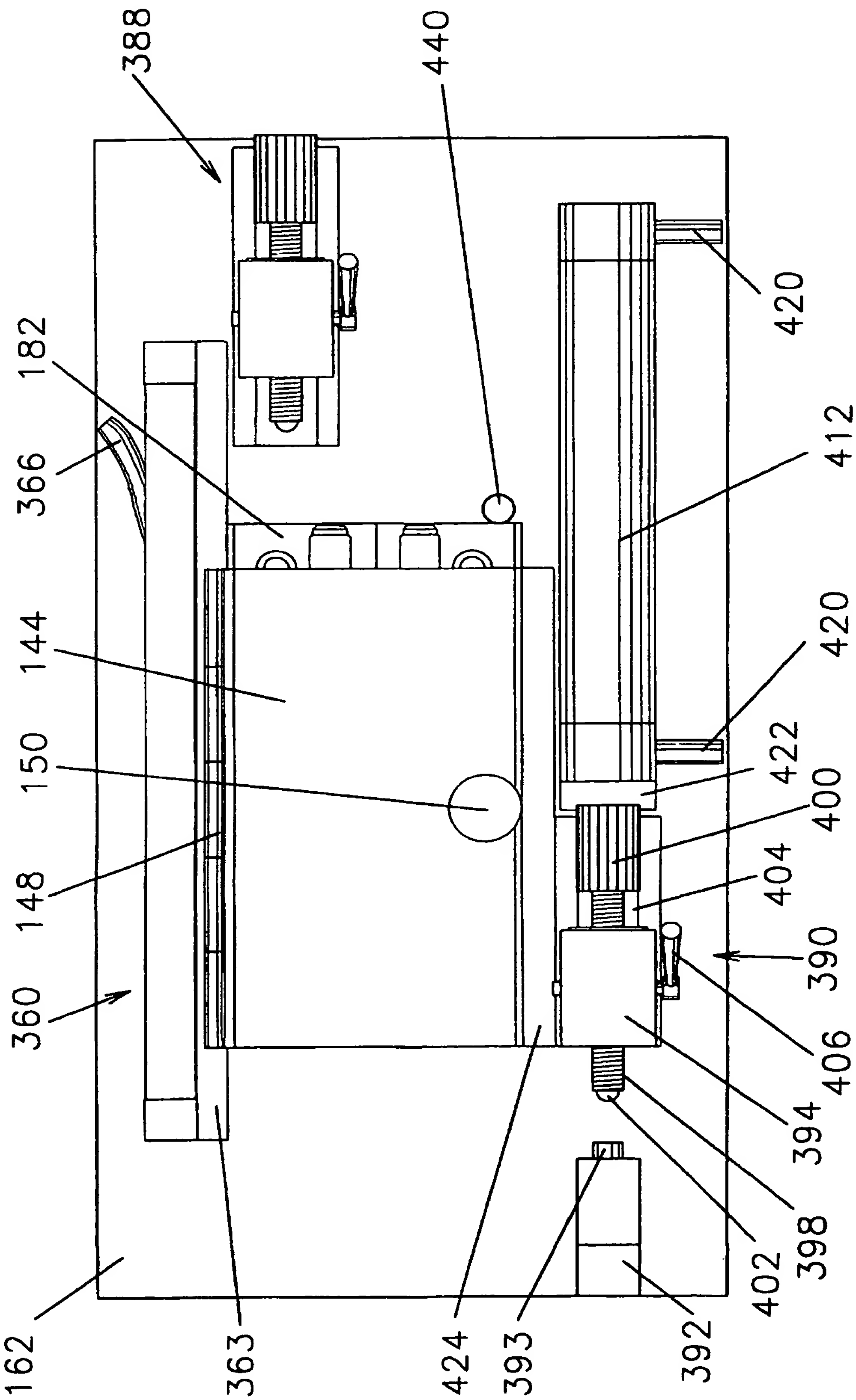
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Fig. 16

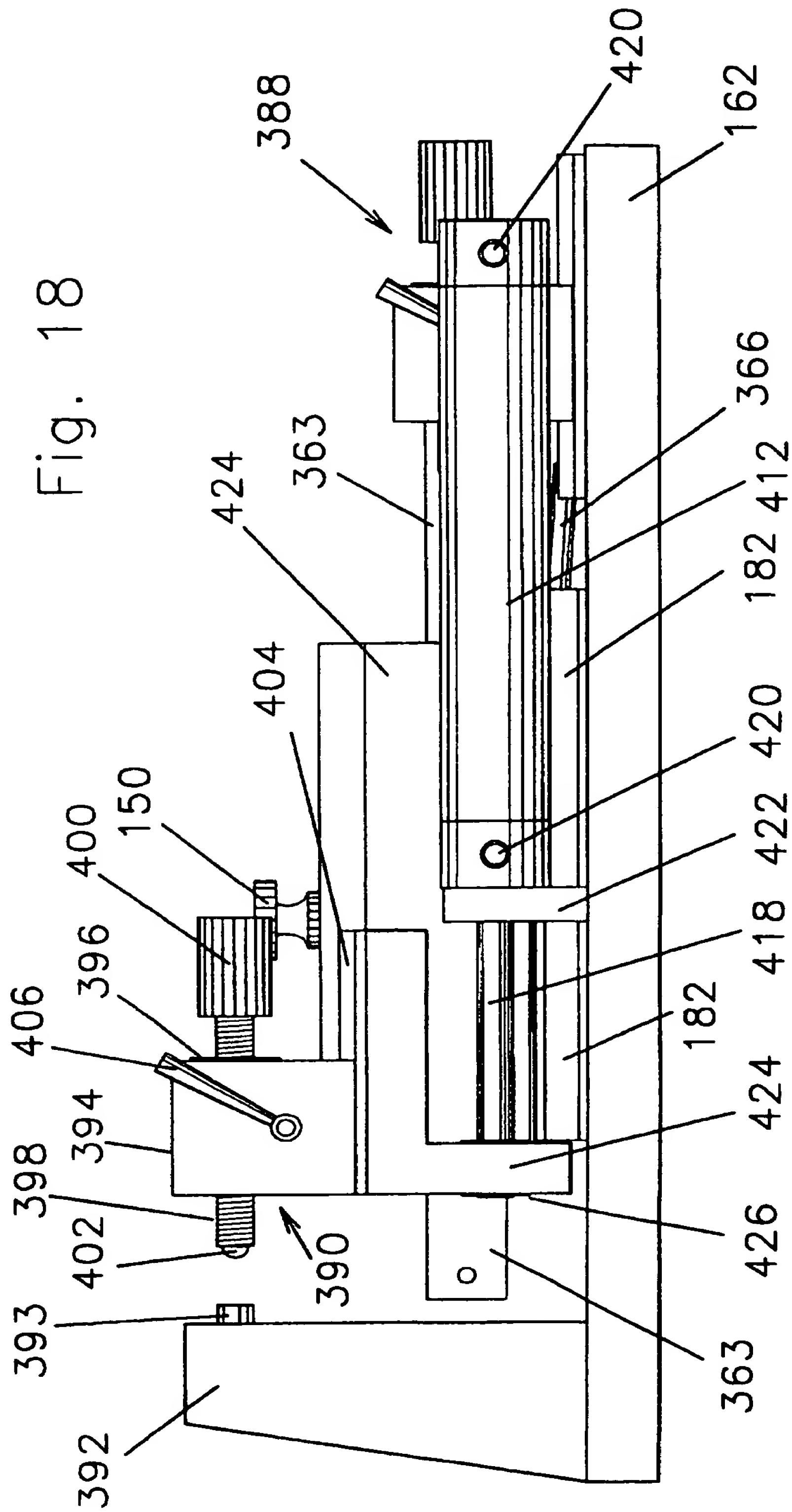
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Fig. 18

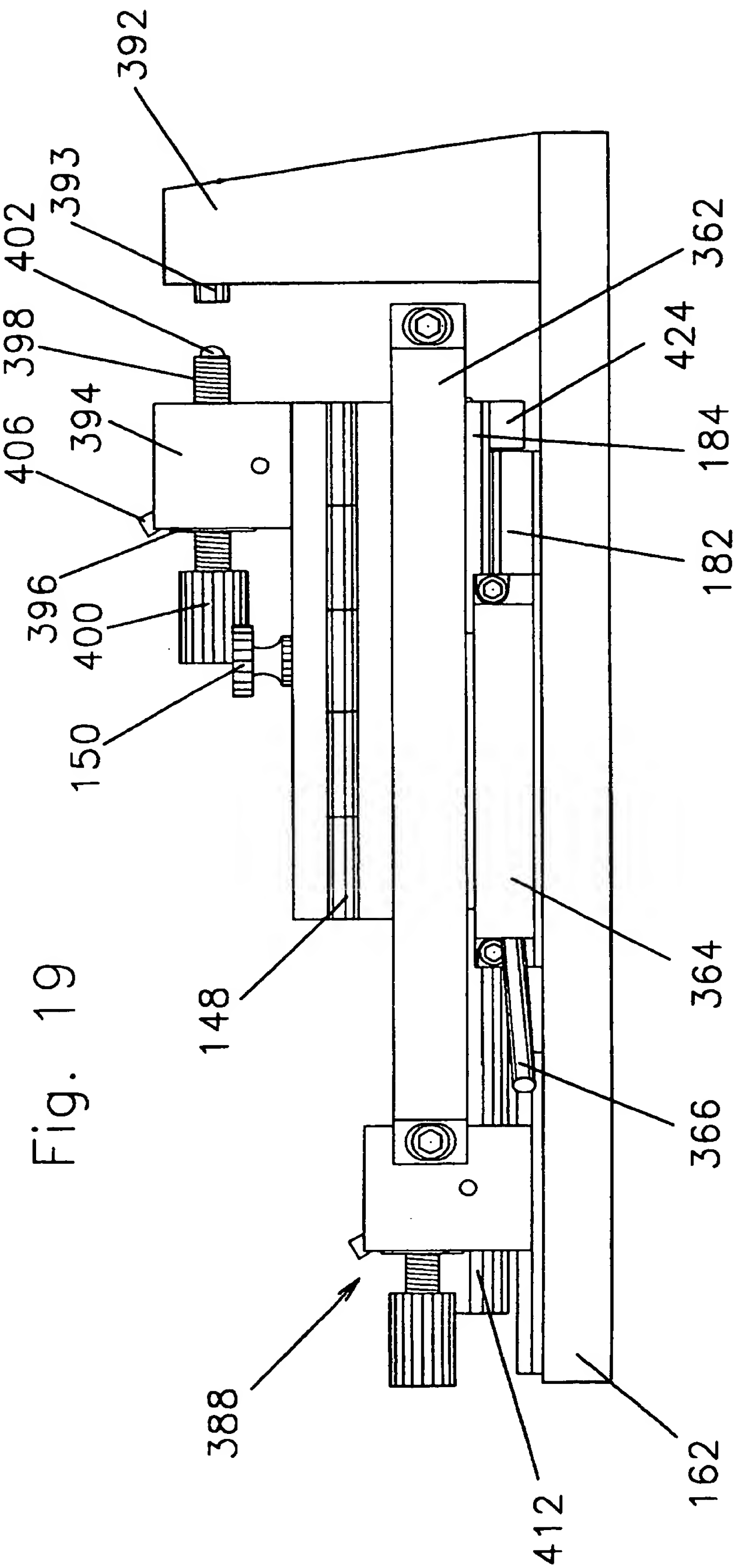
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Fig. 19

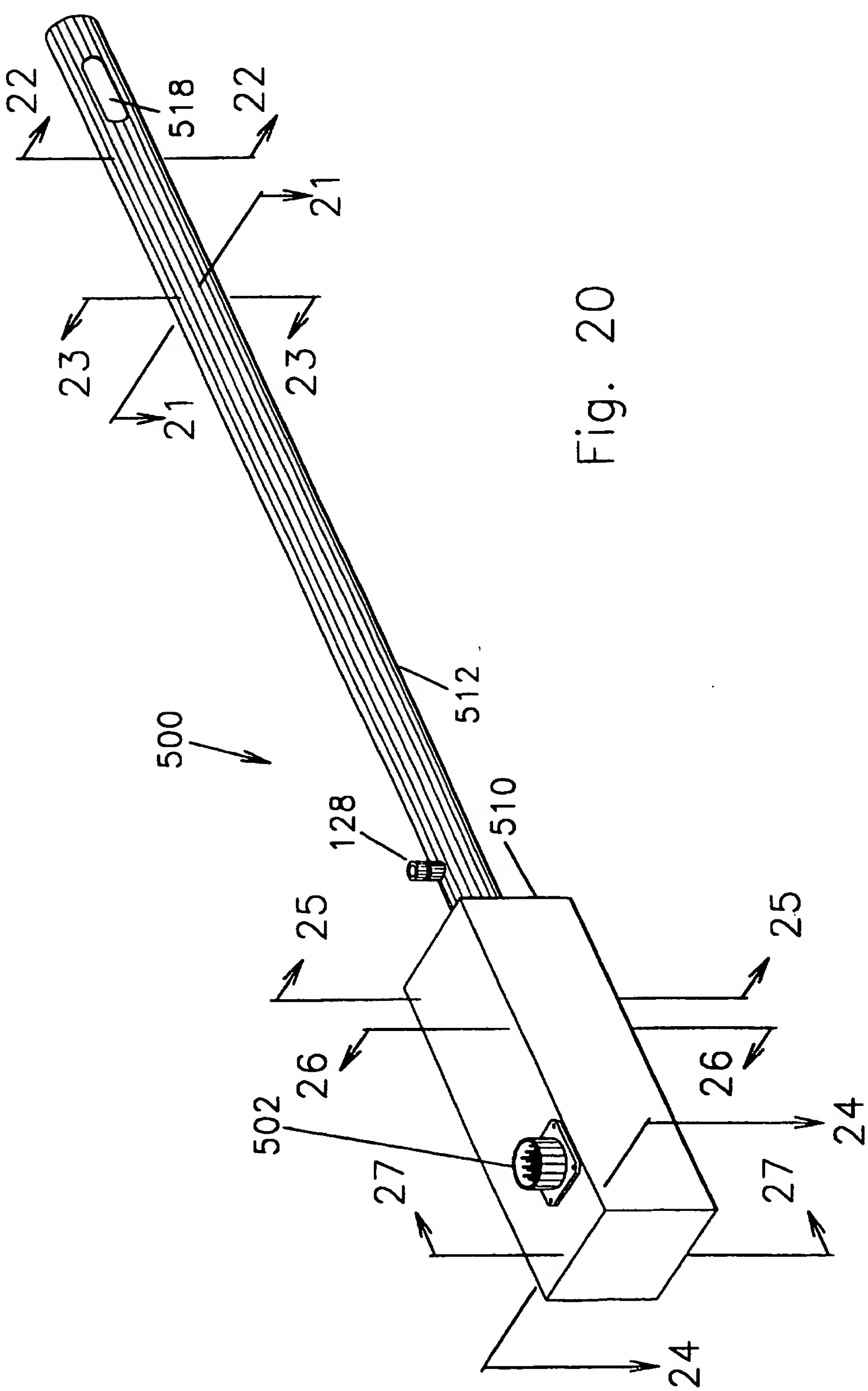

Fig. 20

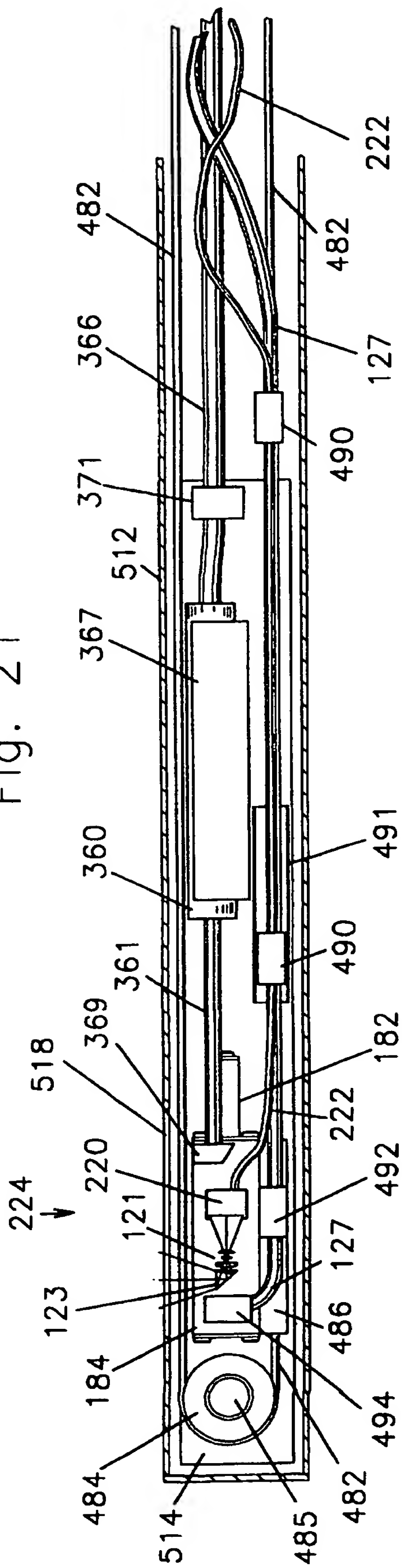

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Fig. 21

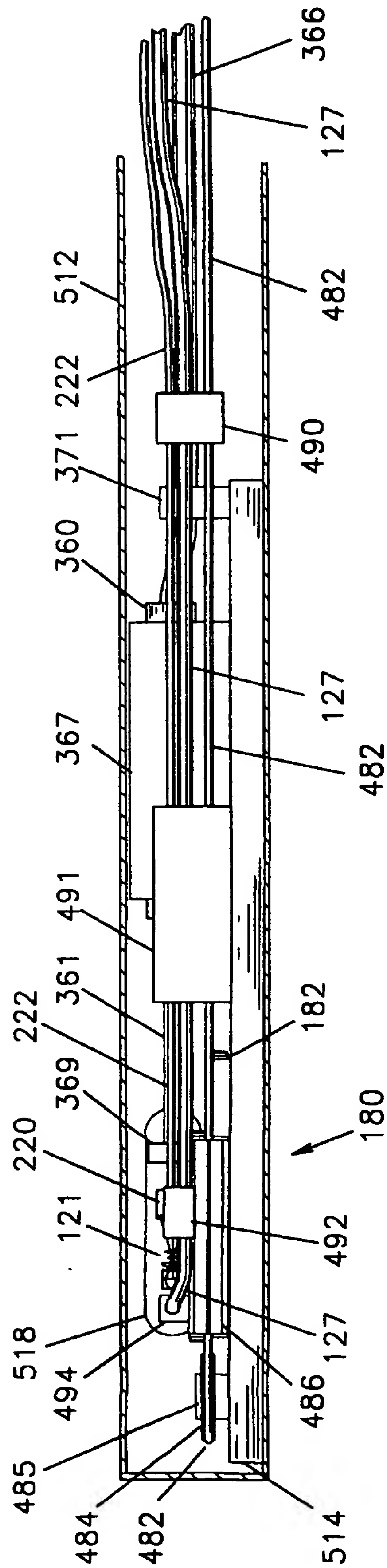

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Fig. 22

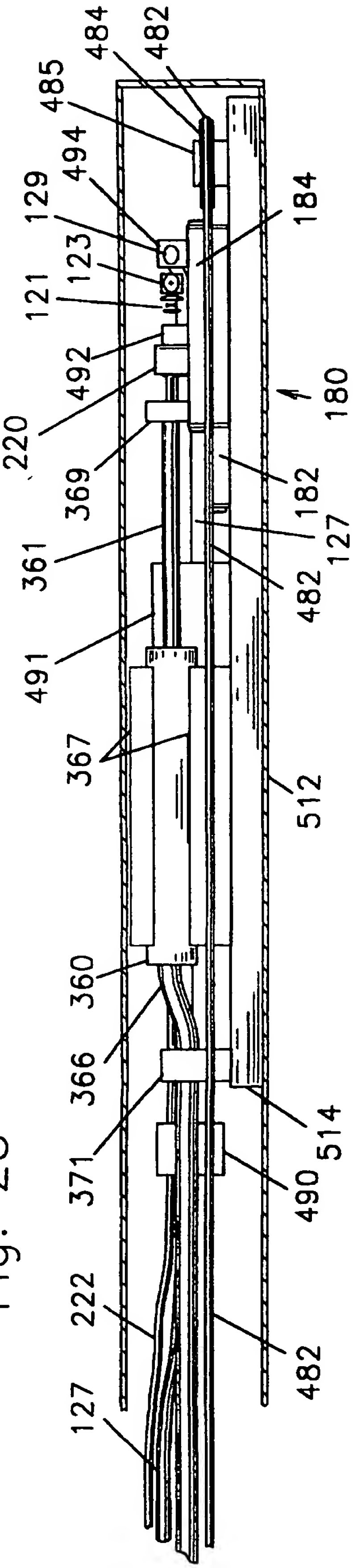
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Fig. 23

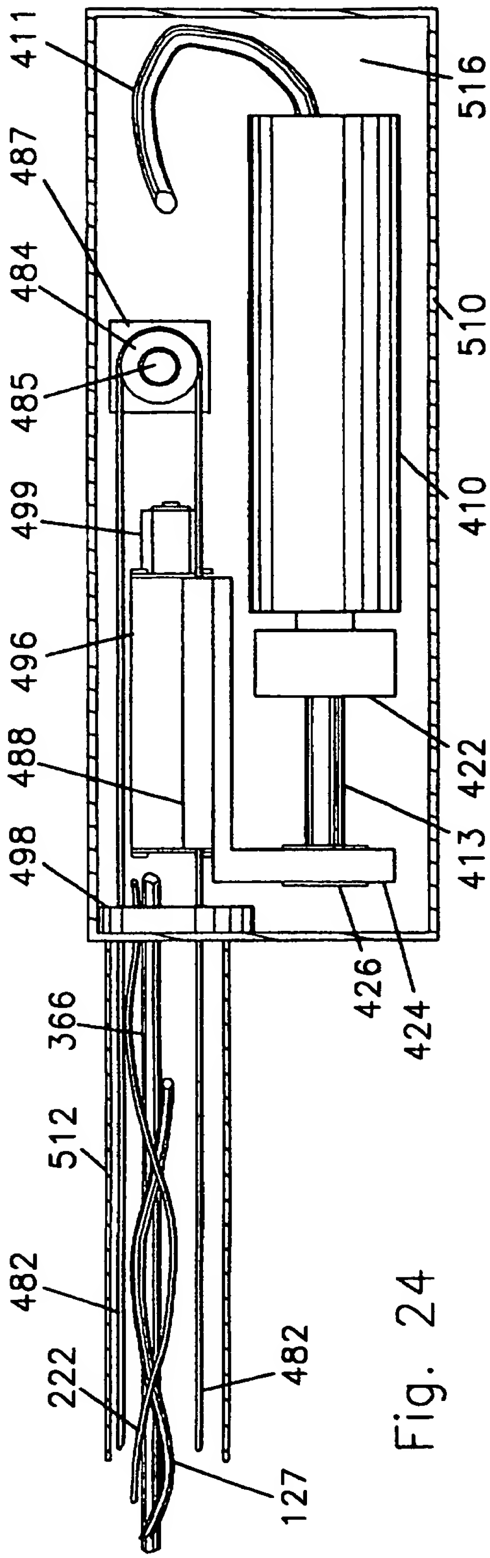
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Fig. 24

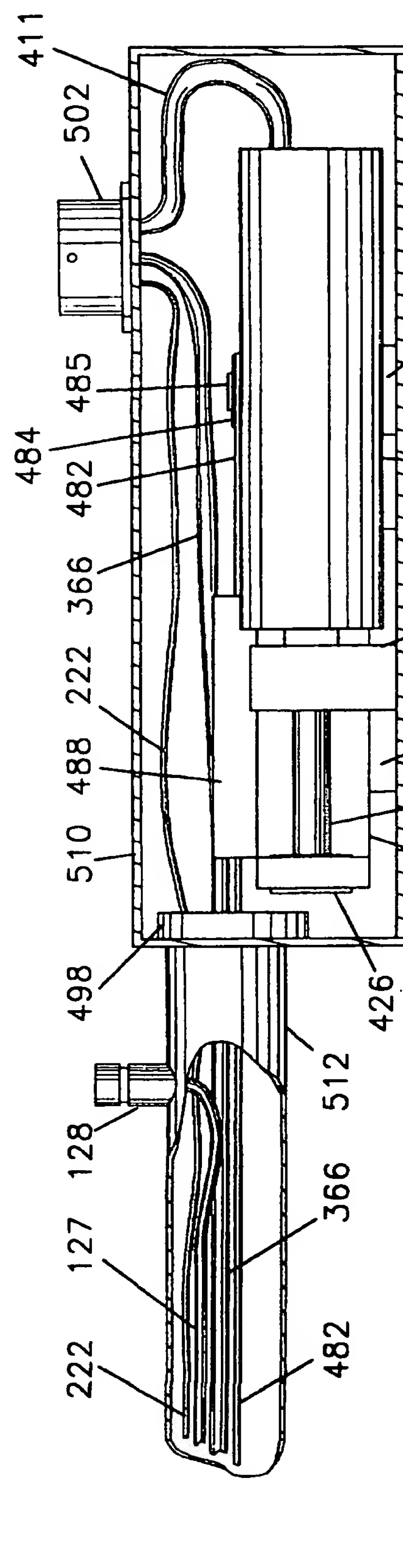
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Fig. 25

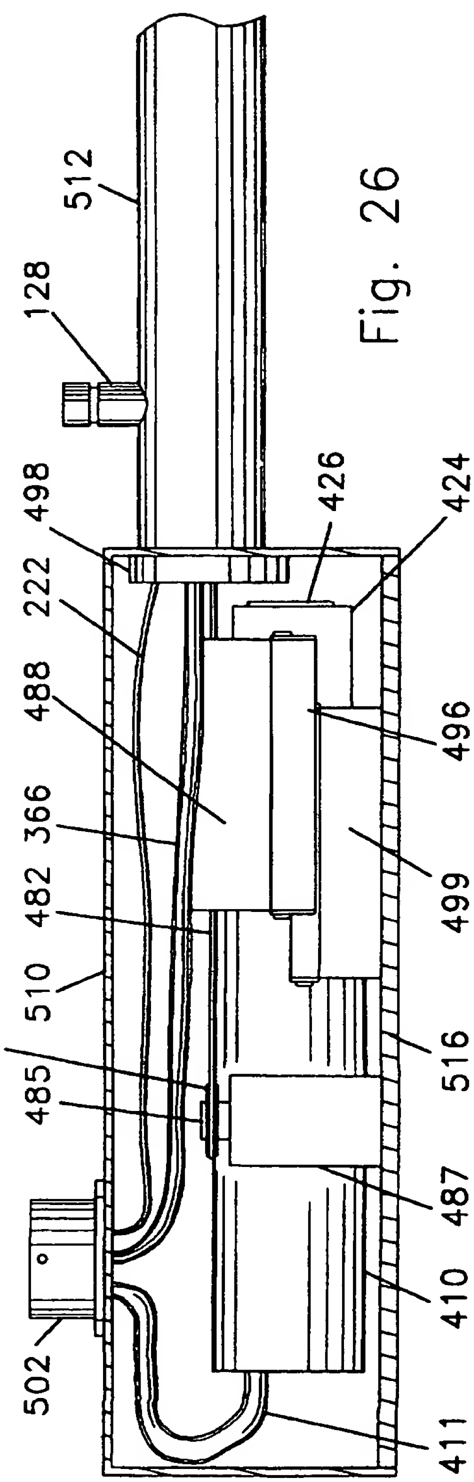
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Fig. 26

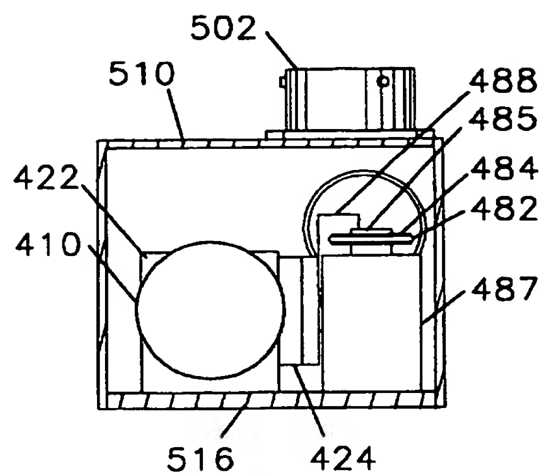


Fig. 27

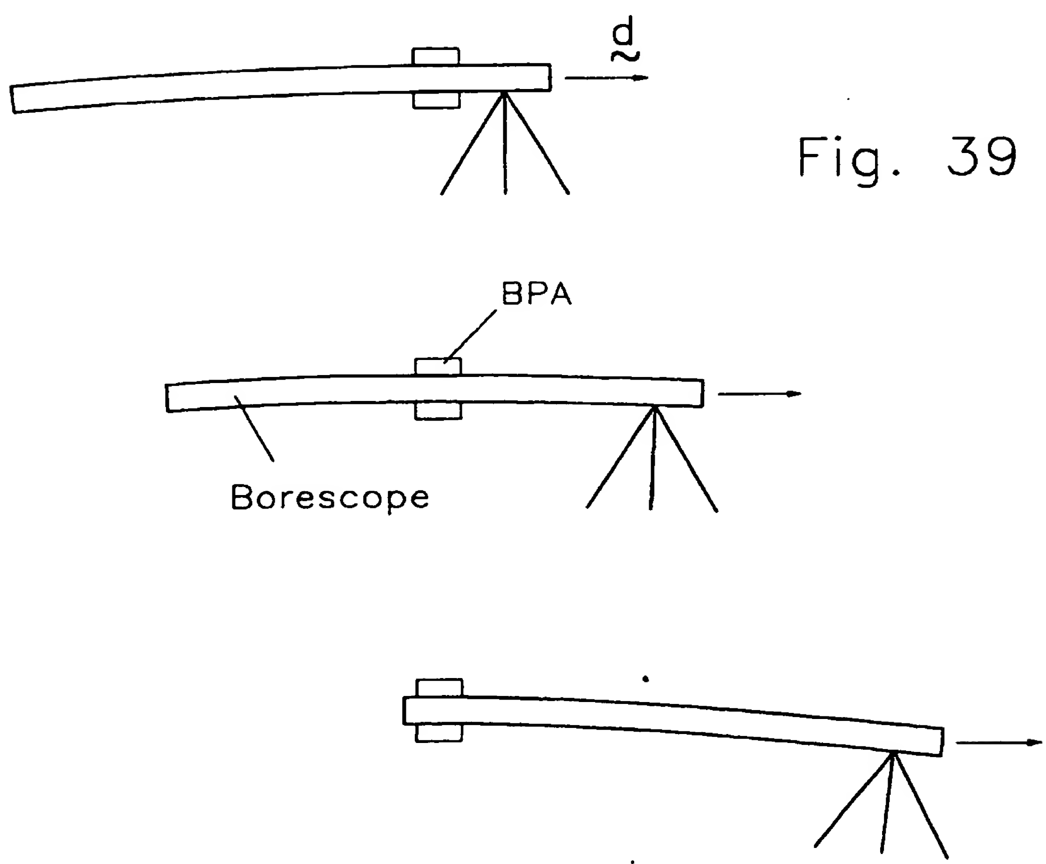
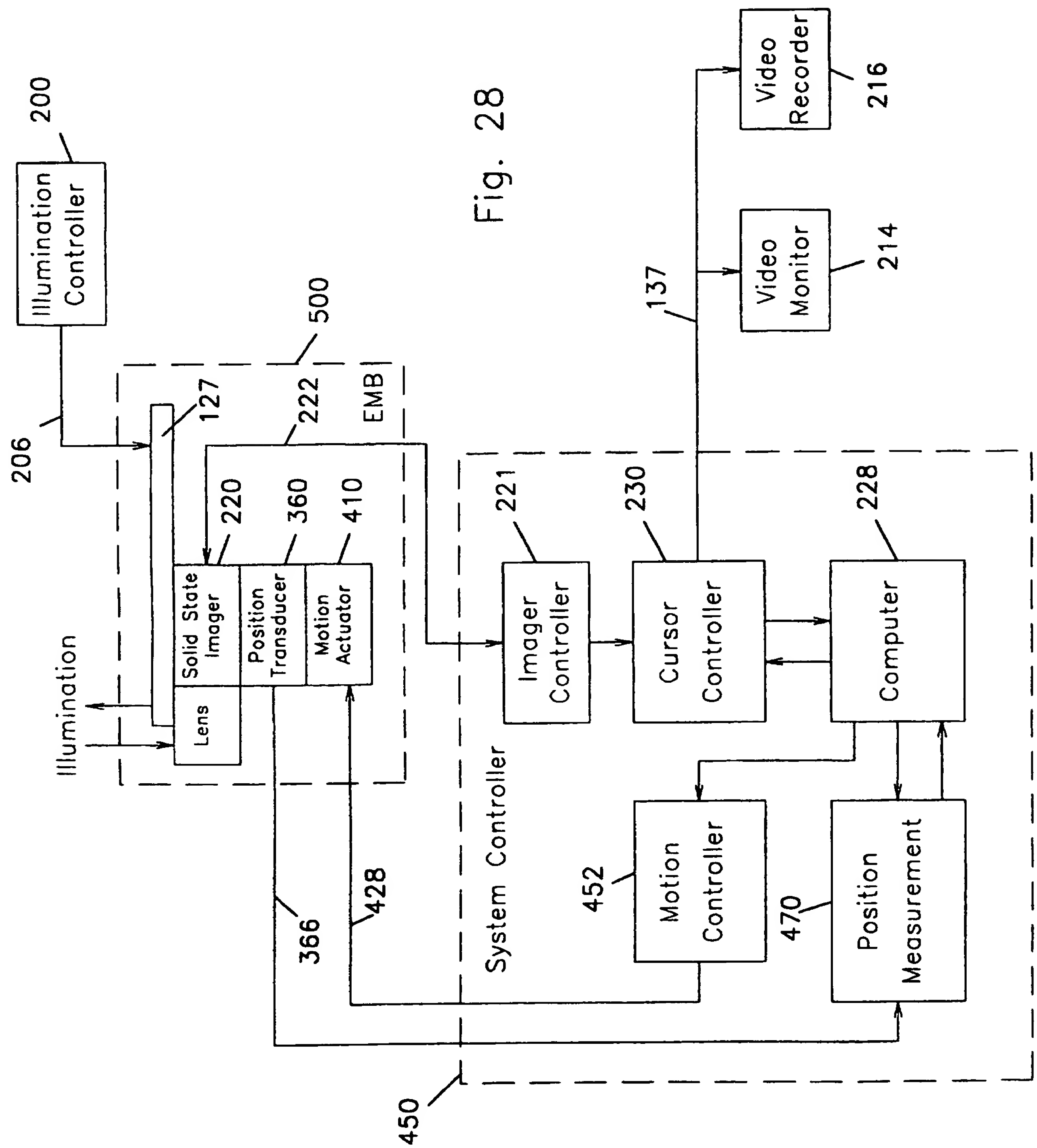


Fig. 39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Solid State Imager
Position Transducer
Motion Actuator
Lens
Illumination
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428
System Controller
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Imager Controller
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Cursor Controller
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Computer
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Motion Controller
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Position Measurement
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Video Monitor
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Video Recorder
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Fig. 28

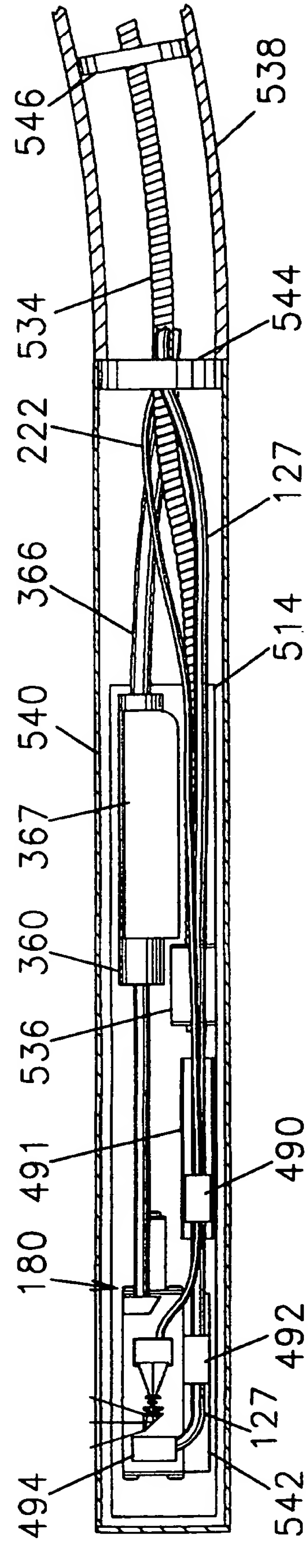
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Fig. 29

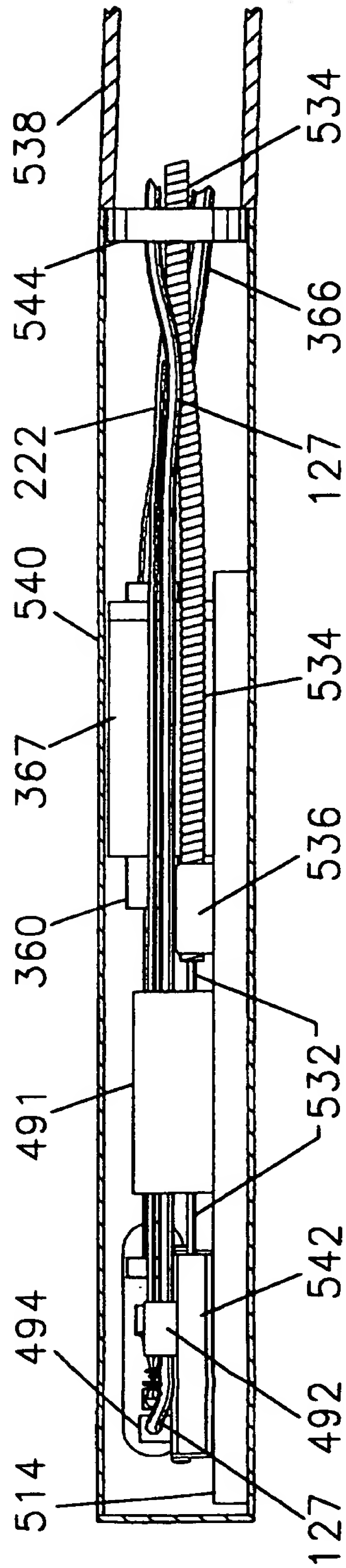
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Fig. 30

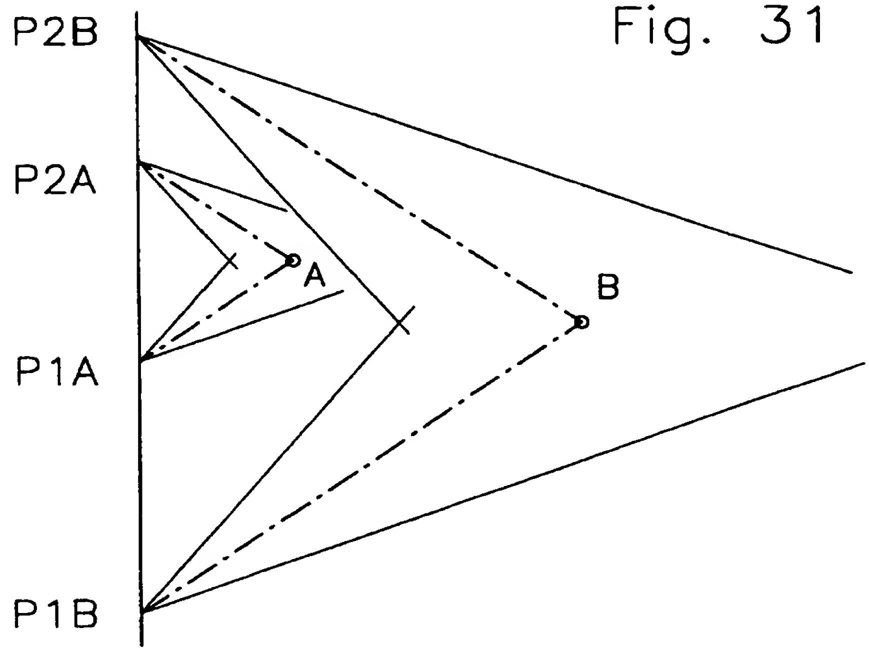


Fig. 31

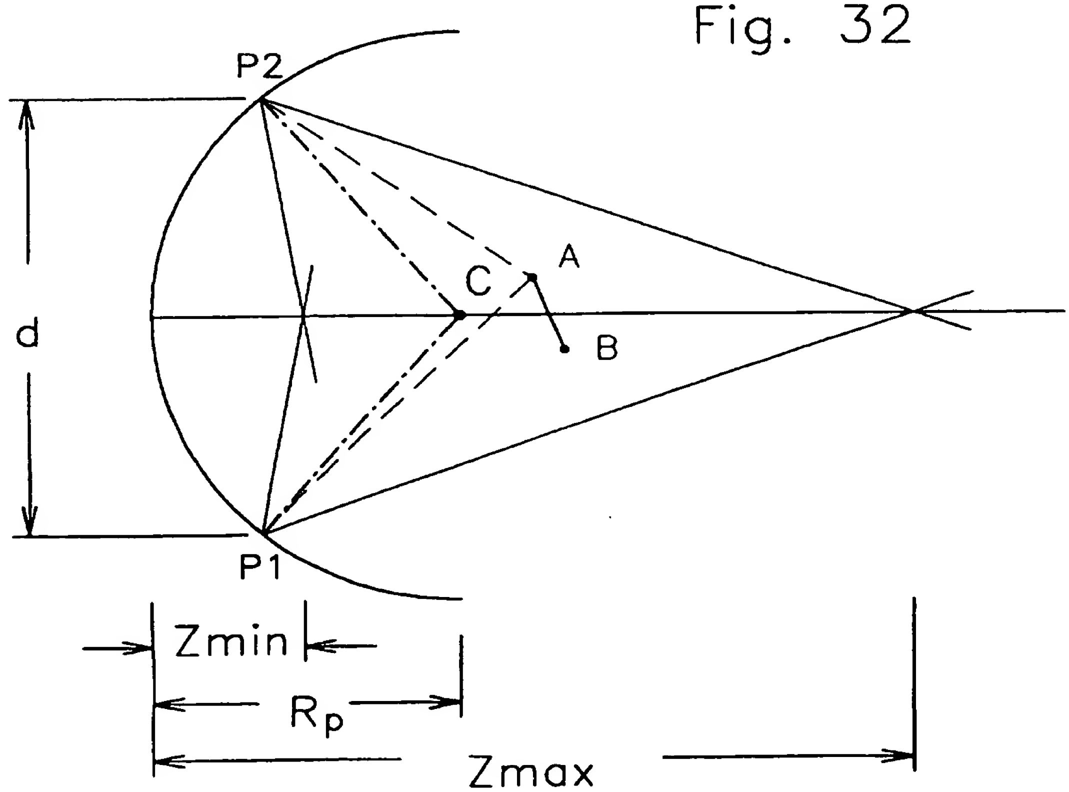


Fig. 32

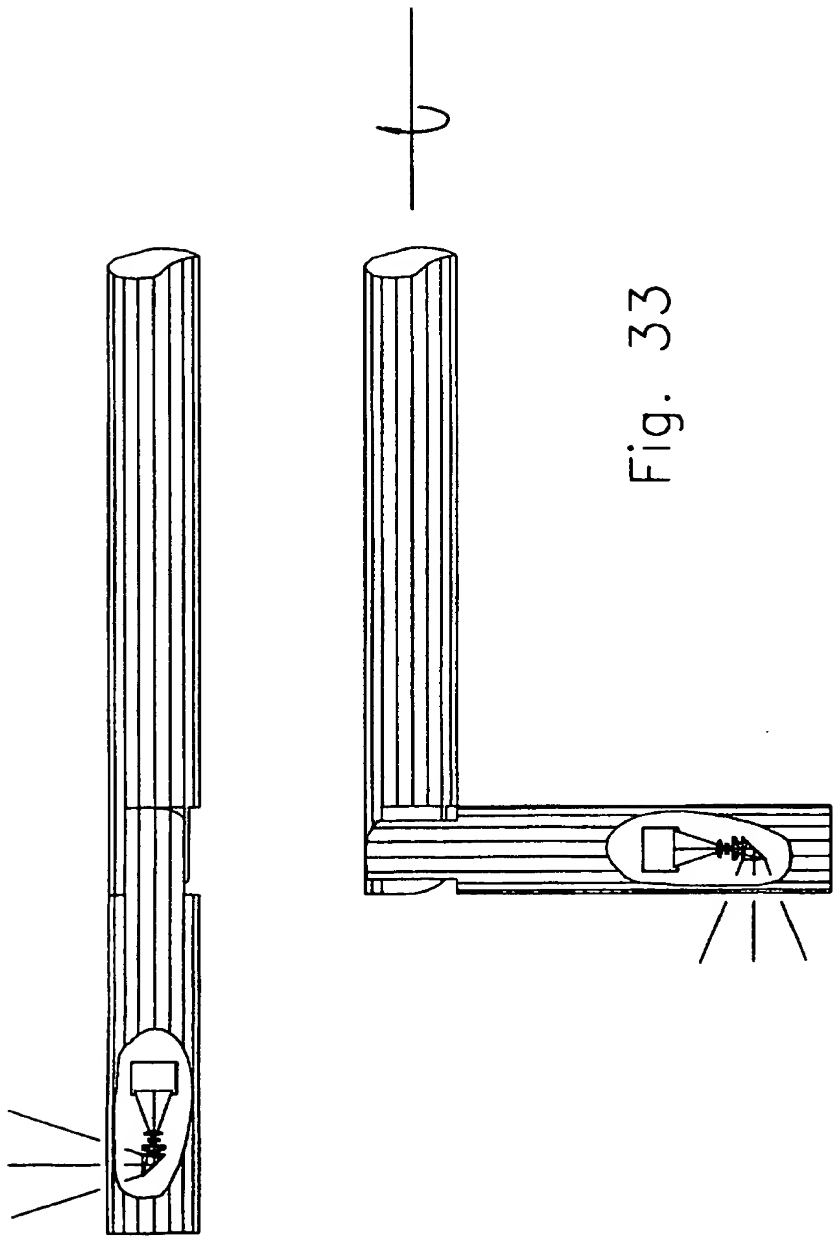


Fig. 33

Fig. 35

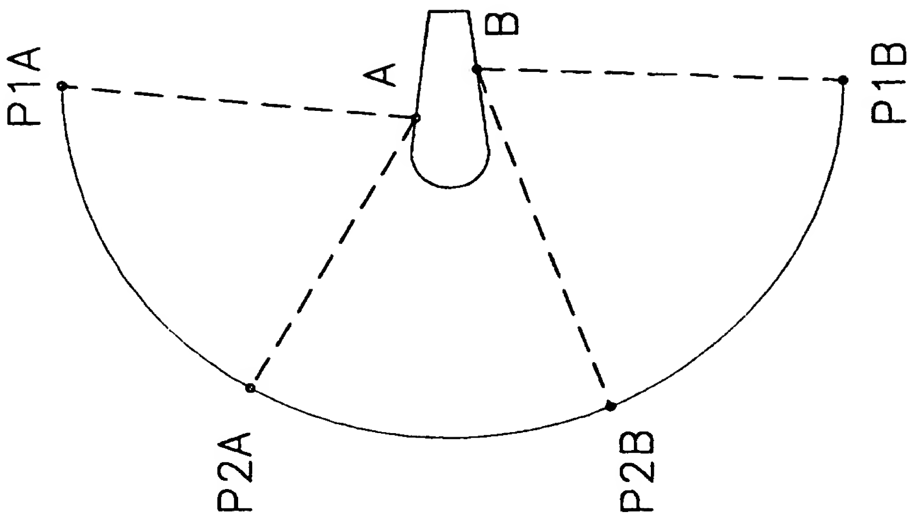
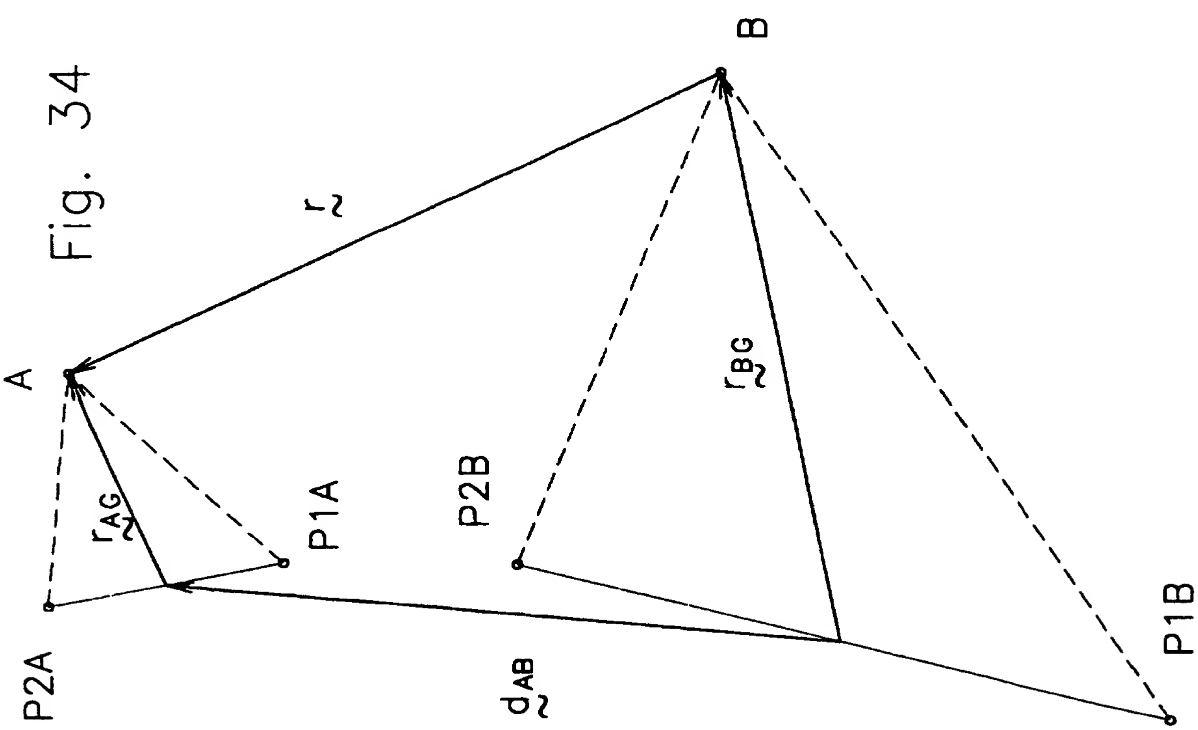


Fig. 34



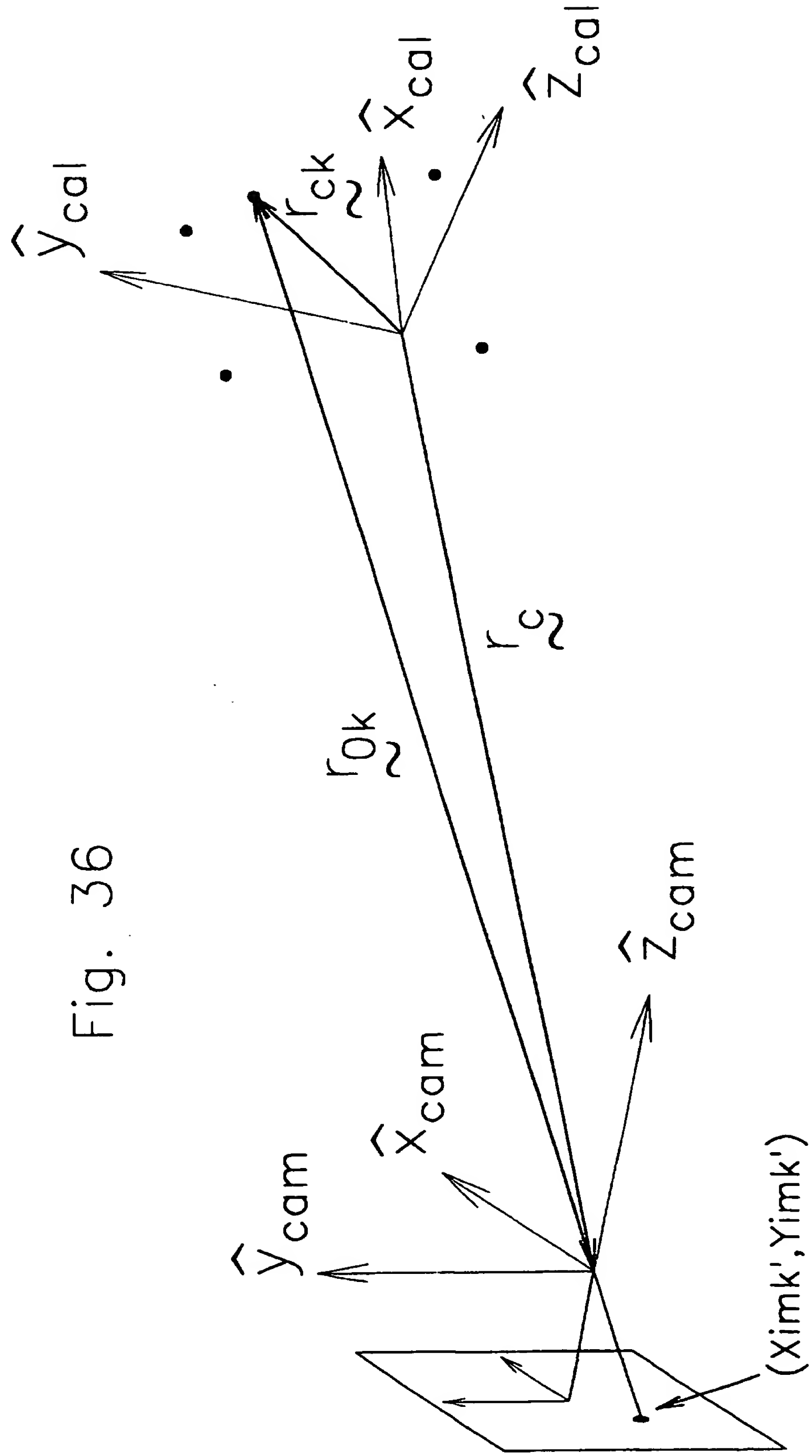

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Fig. 36

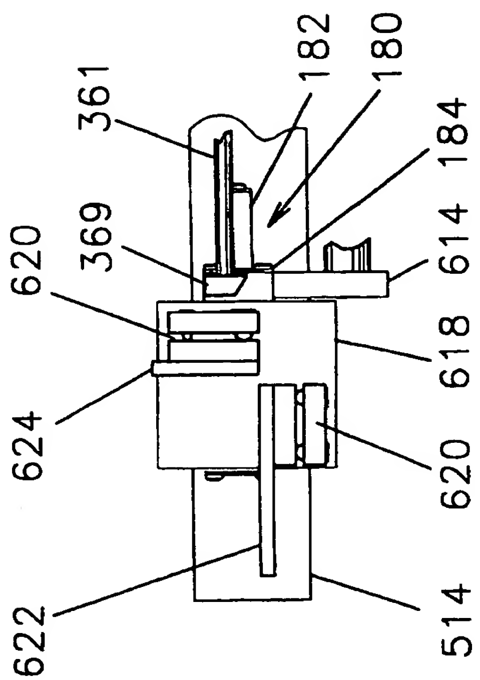
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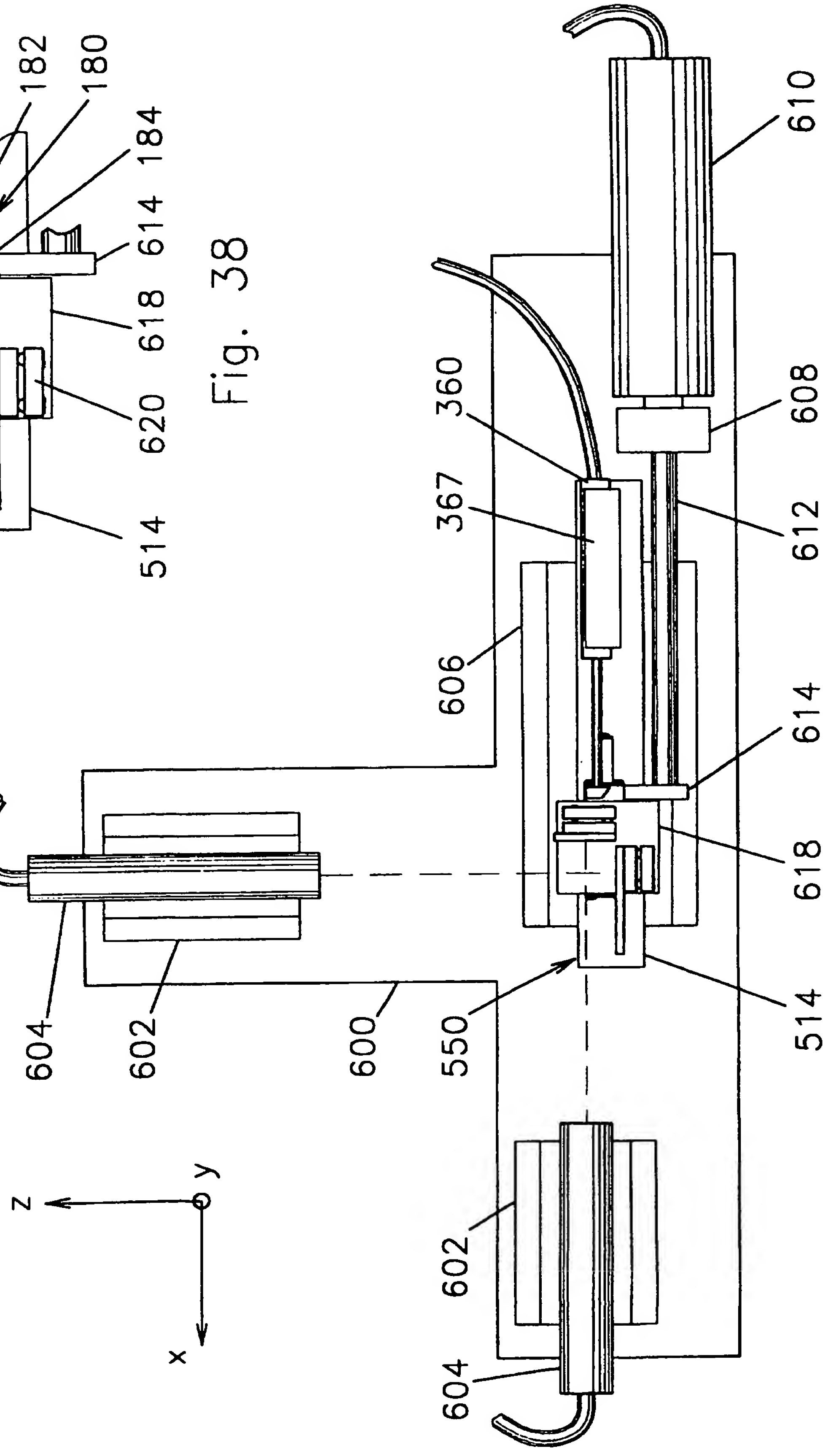
Fig. 38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614
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514
550
600
602
604
602
604
z
y
x

Fig. 37

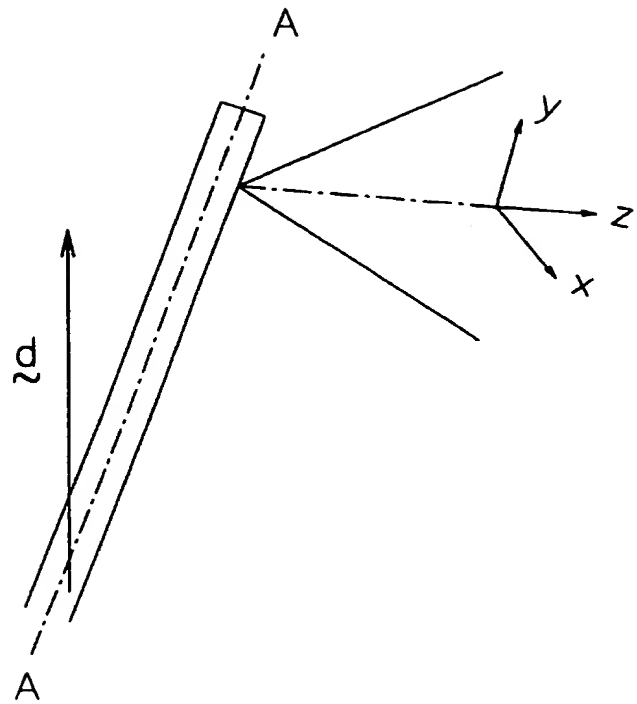


Fig. 40A

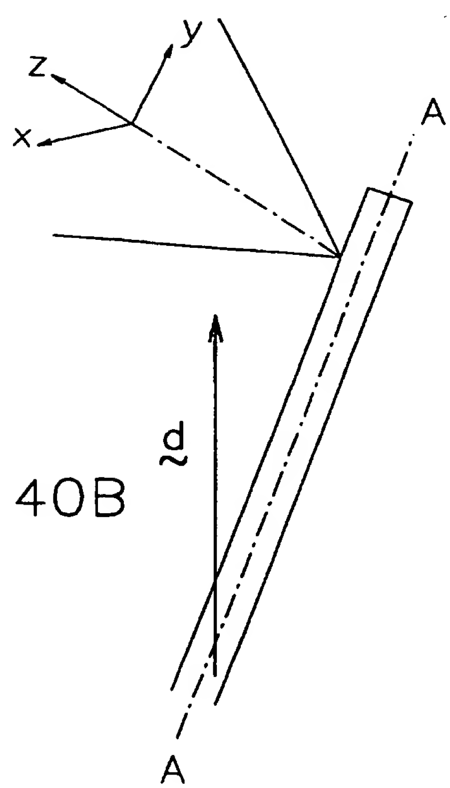


Fig. 40B

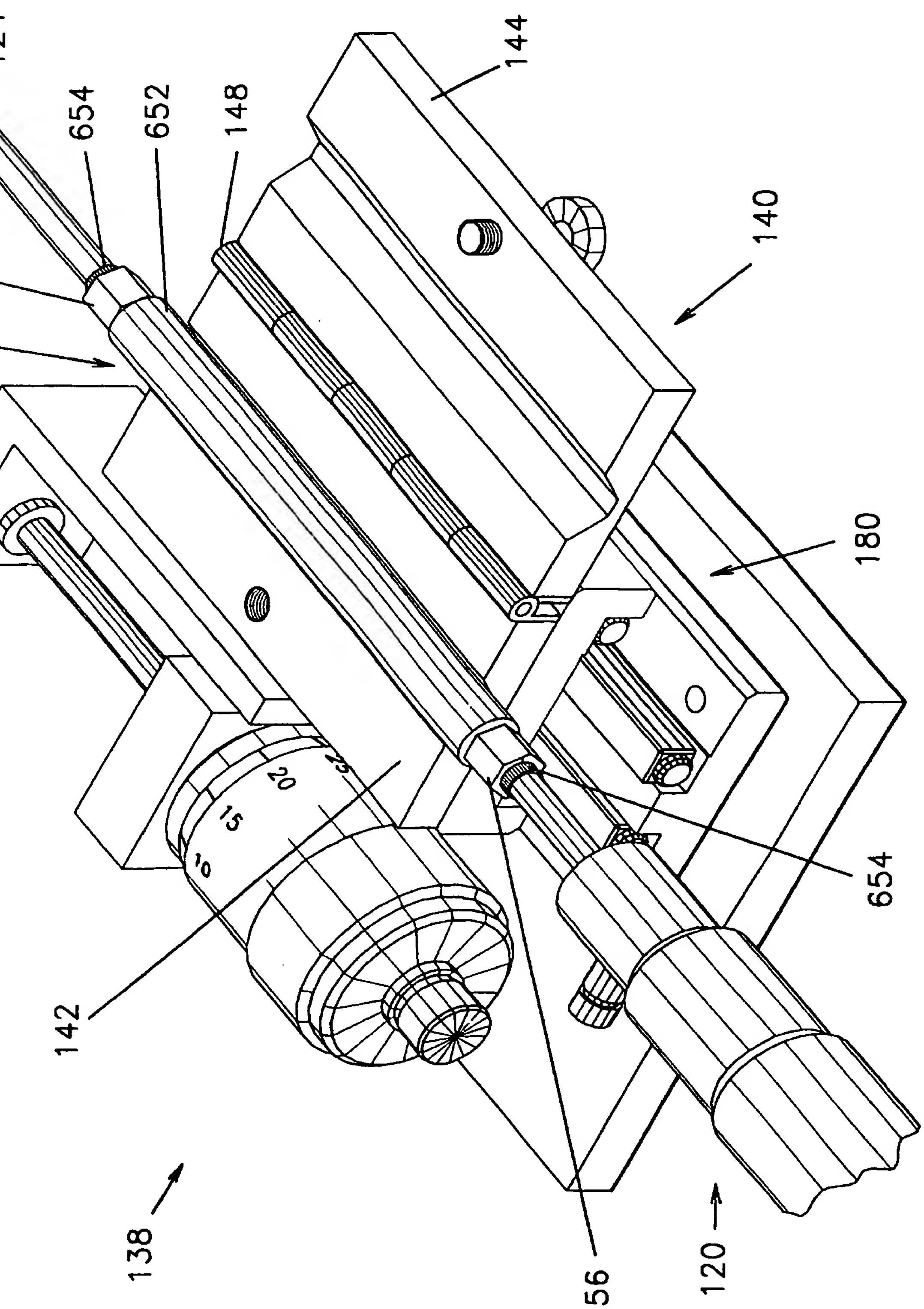


Fig. 41

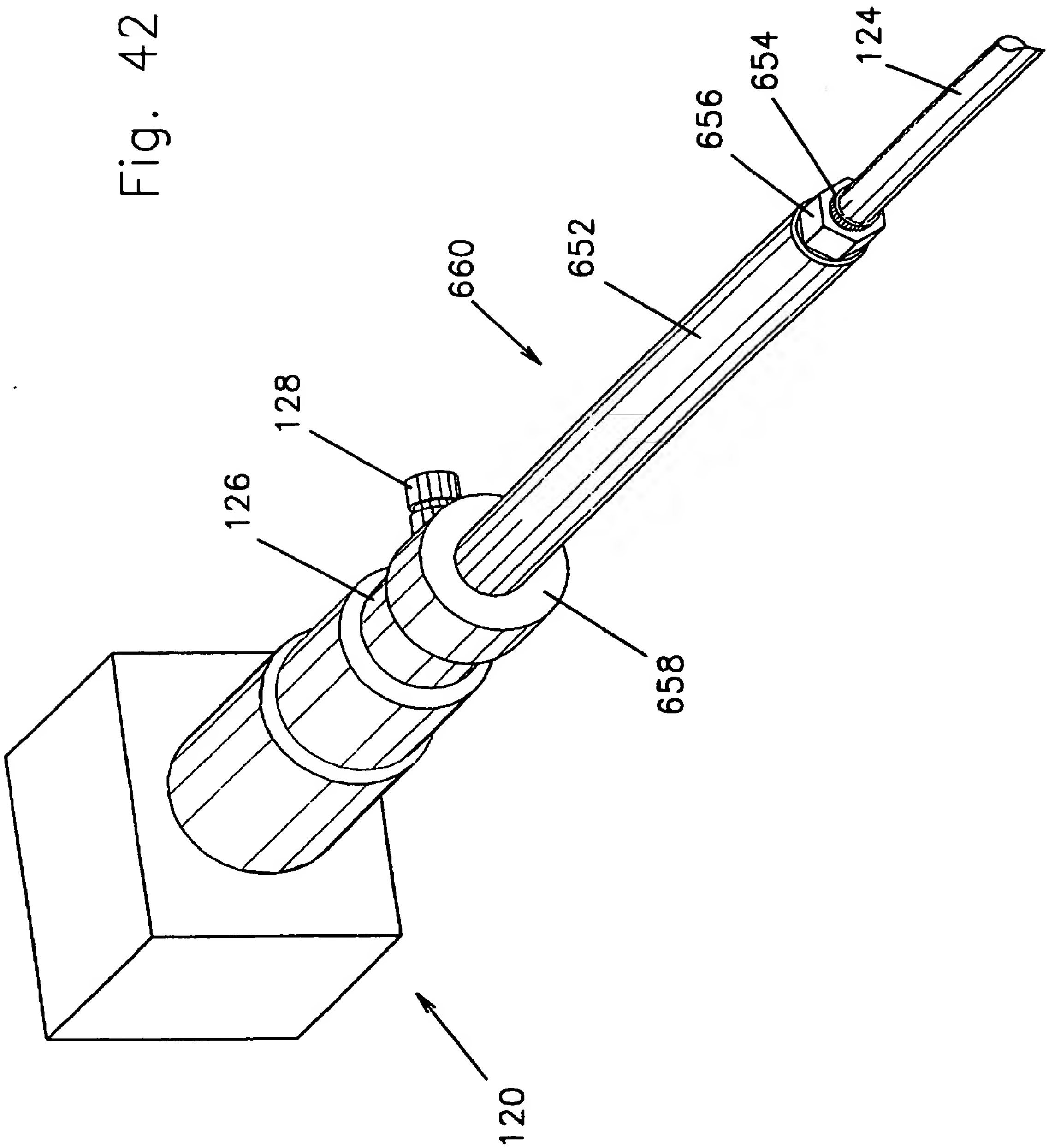


Fig. 42

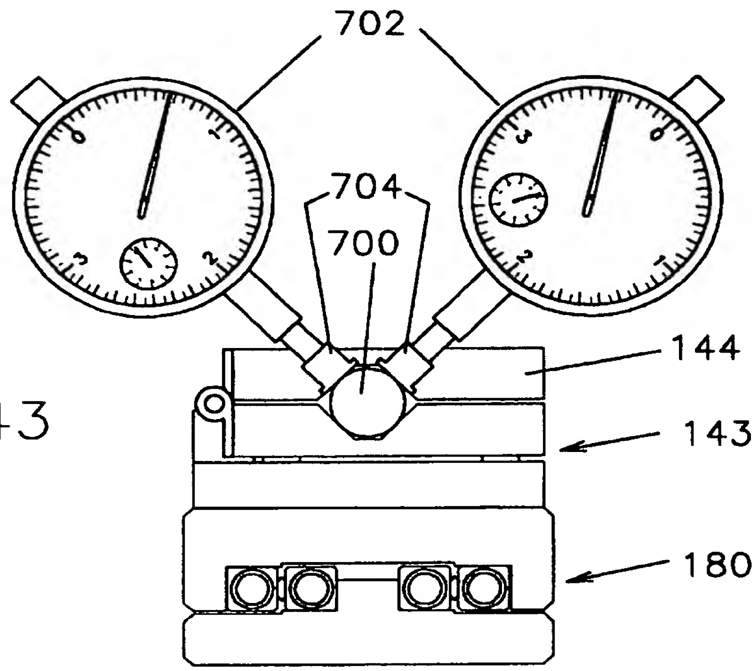


Fig. 43

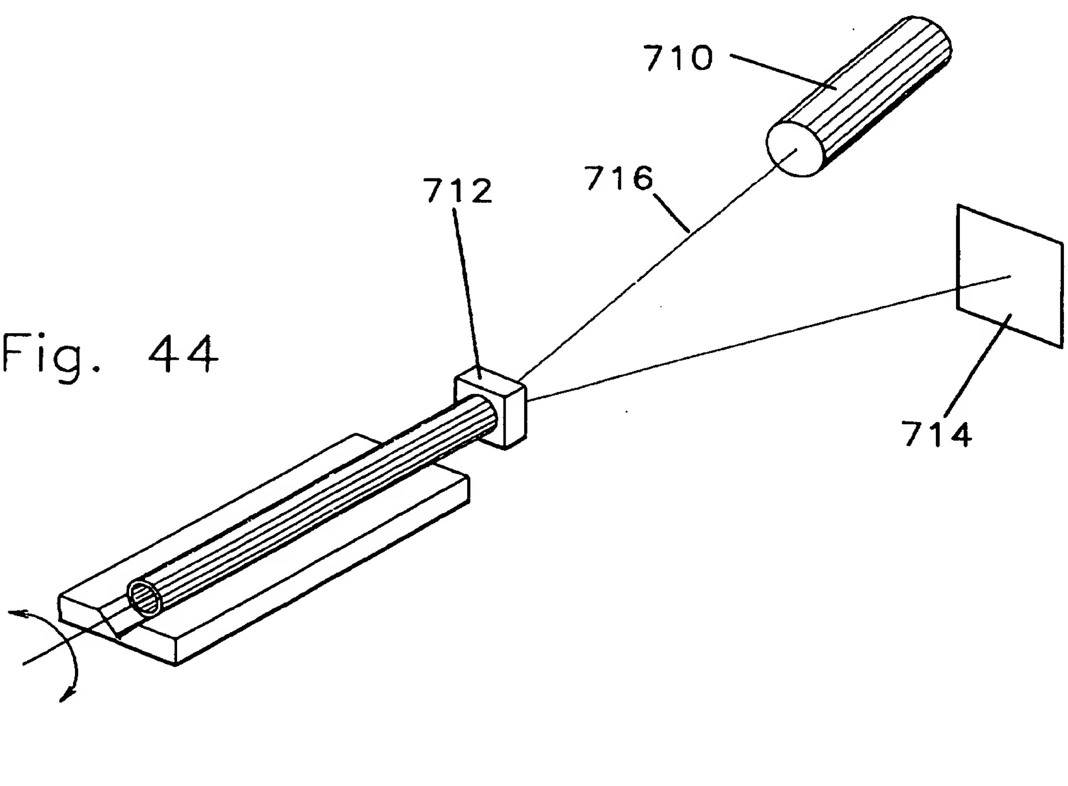


Fig. 44

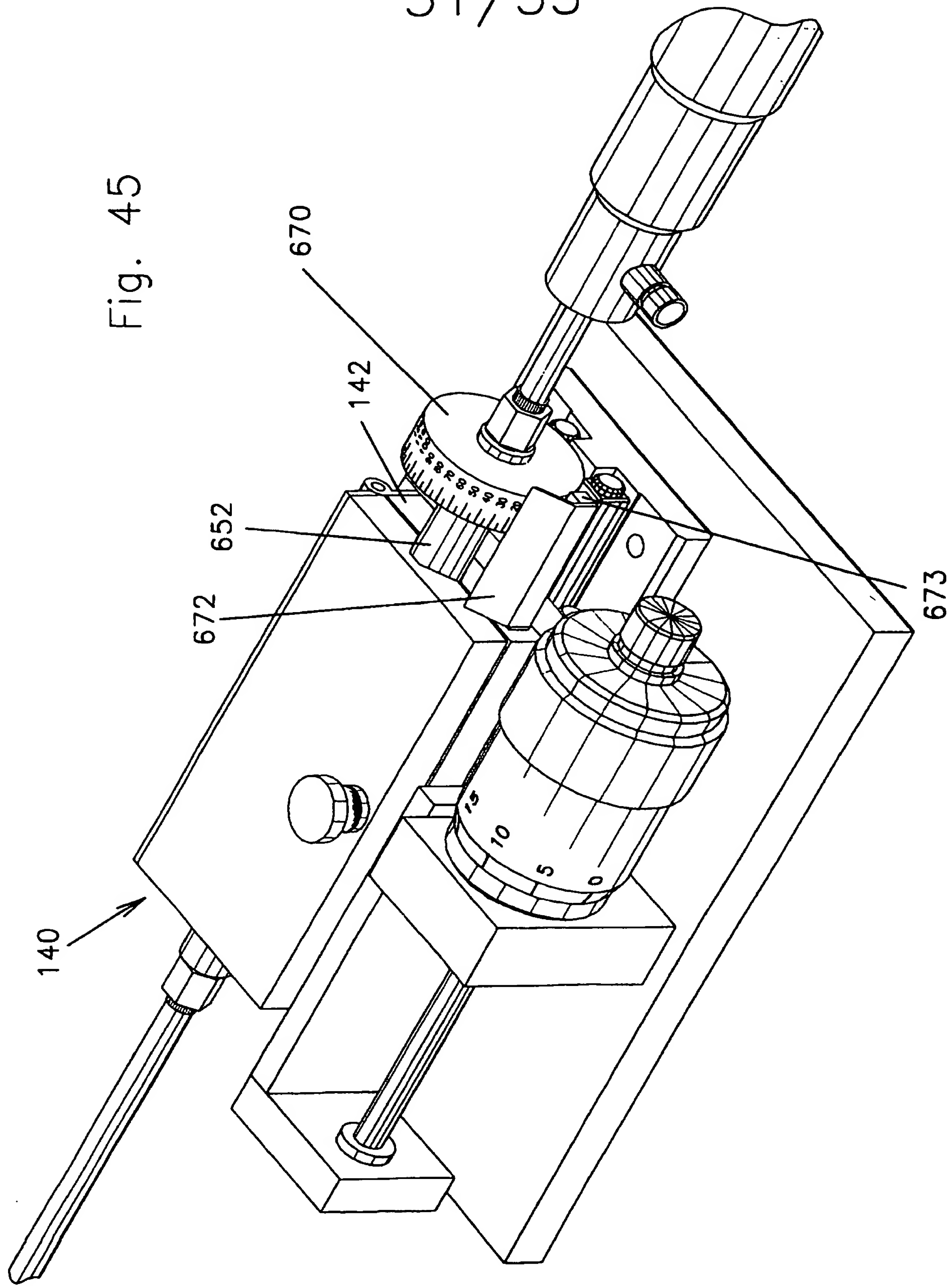
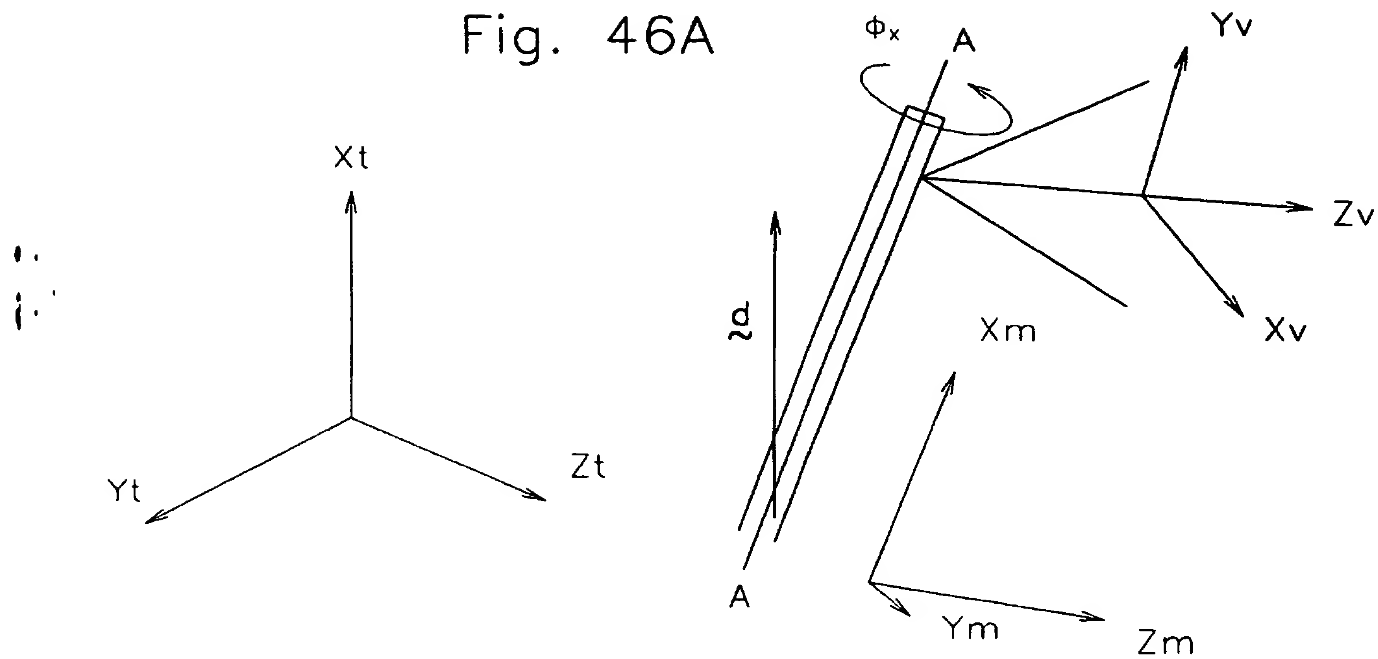


Fig. 45

Fig. 46A



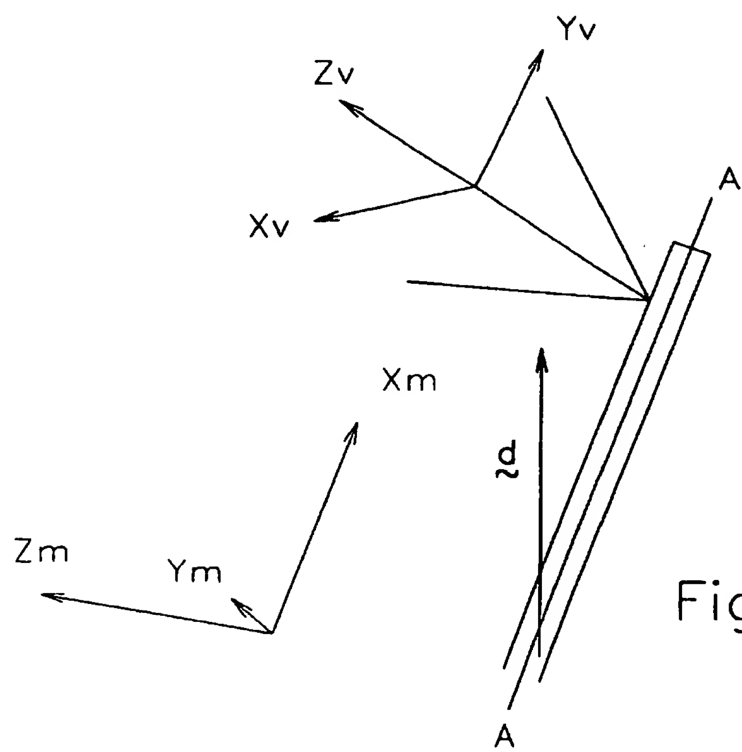


Fig. 46B

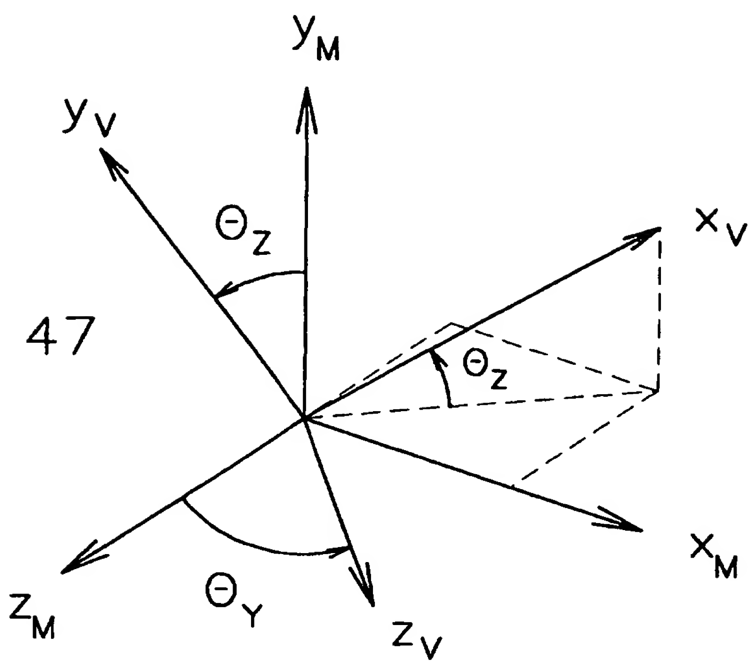


Fig. 47

INTERNATIONAL SEARCH REPORT

Inte .onal Application No
PCT/US 97/15206

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G01B11/02 A61B5/107 G02B23/24

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED
Minimum documentation searched (classification system followed by classification symbols)
IPC 6 G01B A61B G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	N.ODA ET AL.: "Estimation of surface shape from endoscopic image sequence" PROCEEDINGS OF THE SPIE , vol. 1898, 1993, BELLINGHAM, WA, USA, pages 85-92, XP002049182 see the whole document	1,4,18, 20
A	WO 96 20389 A (KEYMED MEDICALS & IND EQUIP) 4 July 1996 see abstract	1

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

° Special categories of cited documents :

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1

Date of the actual completion of the international search	Date of mailing of the international search report
4 December 1997	16/01/1998

Name and mailing address of the ISA	Authorized officer
European Patent Office, P.B. 5818 Patentlaan 2 NL – 2280 HV Rijswijk Tel. (+31-70) 340-2040, Tx. 31 651 epo nl, Fax: (+31-70) 340-3016	Hoekstra, F

INTERNATIONAL SEARCH REPORT

Information on patent family members

Inte ional Application No
PCT/US 97/15206

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
WO 9620389 A	04-07-96	US 5573492 A	12-11-96
		EP 0748435 A	18-12-96

PCT

WORLD INTELLECTUAL PROPERTY ORGANIZATION
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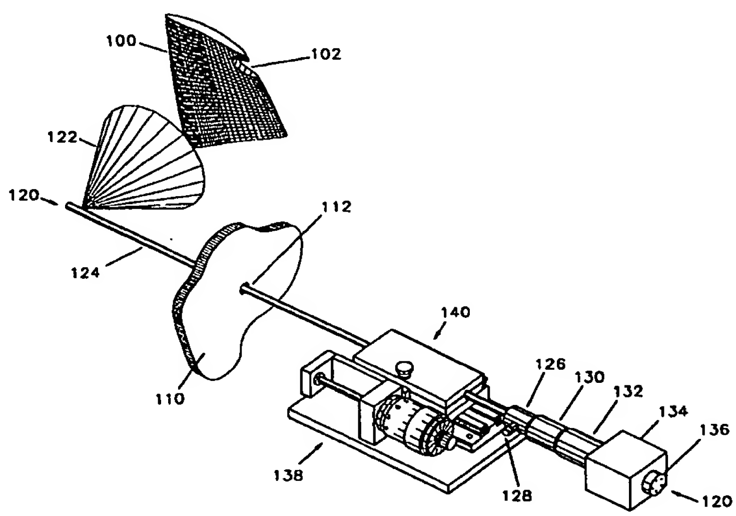
With amended claims.

Date of publication of the amended claims: 16 April 1998 (16.04.98)

(54) Title: APPARATUS AND METHOD FOR MAKING ACCURATE THREE-DIMENSIONAL SIZE MEASUREMENTS OF INACCESSIBLE OBJECTS



(57) Abstract

Spatial locations of individual points on an inaccessible object are determined by measuring two images acquired with one or more cameras which can be moved to a plurality of positions and orientations which are accurately determined relative to the instrument. Once points are located, distances are easily calculated. This new system offers accurate measurements with any convenient geometry, and with existing endoscopic apparatus. It also provides for the measurement of distances which cannot be contained within any single camera view. Systematic errors are minimized by use of a complete and robust set of calibration procedures. A standard measurement procedure automatically adjusts the measurement geometry to reduce random errors. A least squares calculation uses all of the image location and calibration data to derive the true three-dimensional positions of the selected object points. This calculation is taught explicitly for any camera geometry and motion.

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AMENDED CLAIMS

[received by the International Bureau on 9 March 1998 (09.03.98); original claims 1-12, 14 and 16-21 amended; new claim 22 added; remaining claims unchanged (8 pages)]

1. A method of perspective measurement of the three-dimensional size of an inaccessible object using a camera having a field of view, said camera being translated along a substantially straight line from a first viewing position to a second viewing position, characterized in that the first and second viewing positions are selected so that a single point on the object is viewed at an apparent angular position near one edge of the field of view at the first viewing position, and at substantially the same apparent angle on the other side of the field of view at the second viewing position, thereby minimizing the random error in the measurement.

2. A method of perspective measurement of the three-dimensional size of an inaccessible object using a camera, said camera being translated along a substantially straight line from a first viewing position to a second viewing position, characterized in that any errors in the translational motion of the camera are determined in a calibration process and in that these errors are then also taken into account in the measurement result.

3. A method of perspective measurement of the three - dimensional distances between selected points on an inaccessible object using a rigid borescope, said borescope being translated along a substantially straight line from a first viewing position to a second viewing position, wherein said borescope forms a first optical image of said object at said first viewing position and a second optical image of said object at said second viewing position, and wherein each of said selected points on said object is individually located in each of said first and second images, characterized by the use of a fully three - dimensional least squares estimation procedure to determine the measurement result.

4. An apparatus for measuring three - dimensional distances between individual user selected points on an inaccessible object, comprising at least one probe body and additionally characterized by:
   (a) one or more cameras located near the distal ends of said at least one probe body, said cameras forming images of said selected points on said object;
   (b) motion means for moving at least one of said one or more cameras with respect to its probe body, said motion means providing a plurality of relative camera positions for each of said cameras;
   (c) orientation means for providing a relative spatial orientation for each of said cameras at each of said relative positions;
   (d) position determination means, for determining the relative positions of each of said one or more cameras, said position determination means also producing camera position data which is provided to a computing means;
   (e) orientation determination means, for determining the relative orientations of each of said one or more cameras, said orientation determination means also producing camera orientation data which is provided to the computing means;
   (f) image measurement means, for measuring the positions of said images of said user selected points on said object, said image measurement means also producing point position data which is provided to the computing means; and

(g) computing means that receives said camera position data and said camera orientation data and said point position data, said computing means being adapted to calculate the three - dimensional distances between said user selected points on said inaccessible object.

5. The apparatus of claim 4 characterized in that the orientation means is combined with the motion means such that said relative orientations are predetermined functions of said relative positions, thereby making it possible to eliminate the use of said orientation determination means except during calibration, or in that said plurality of relative camera positions constitutes a set of fixed relative positions, thereby making it possible to eliminate the use of said position determination means except during calibration.

6. The apparatus of claims 4 or 5 characterized in that said relative camera positions all lie along a substantially straight line, or along a substantially circular arc.

7. The apparatus as claimed in any one of claims 4, 5 or 6 characterized in that said relative camera spatial orientations are all substantially the same.

8. The apparatus of claim 6 characterized in that said relative camera positions lie along said circular arc, said circular arc having a center of curvature, and in that each of said cameras has an optical axis, and in that the orientation of each of said one or more cameras is coupled to its position along the arc so that said optical axis is always substantially aligned with said center of curvature of the arc, or in that the orientation of each of said one or more cameras is such that said optical axis is aligned substantially perpendicular to the plane containing the arc.

9. A method of determining the three - dimensional distance between a pair of points on an object, characterized by the steps of:

(a) providing one or more cameras, each of which has an internal coordinate system and an effective focal length, and further providing a plurality of relative camera positions for each of said cameras, wherein each of said cameras has a spatial orientation at each of said relative positions, and wherein said relative positions and said spatial orientations are determined in an external coordinate system, such that said relative camera positions form camera location vectors in said external coordinate system;

(b) acquiring a first image of a first point of said pair of points on the object with one of said one or more cameras located at a first viewing position, said camera having a first spatial orientation at said first viewing position, thereby defining a first measurement coordinate system which is coincident with the internal coordinate system of said camera at said first viewing position;

(c) acquiring a second image of said first point of said pair of points on the object with one of said one or more cameras located at a second viewing position, said camera having a second spatial orientation at said second viewing position, thereby defining a second measurement coordinate system which is coincident with the internal coordinate system of said camera at said second viewing position;

(d) measuring the coordinates of said first image of said first point in said first measurement coordinate system and measuring the coordinates of said second image of said first point in said second measurement coordinate system;

(e) correcting the measured coordinates of the first image of said first point to adjust for any distortion of the camera located at the first viewing position, and correcting the measured coordinates of the second image of said first point to adjust for any distortion of the camera located at the second viewing position, thereby producing first and second final first point image coordinates for said first and second viewing positions in said first and second measurement coordinate systems;

(f) multiplying the first final first point image coordinates by the mathematical inverse of the effective focal length of the camera located at the first viewing position and multiplying the second final first point image coordinates by the mathematical inverse of the effective focal length of the camera located at the second viewing position, to determine the mathematical tangents of the angles at which said first point is viewed in said first and second measurement coordinate systems;

(g) forming a least squares estimate of the three dimensional coordinates of said first point in a first temporary measurement coordinate system, thereby forming an estimate of the vector location of said first point in said first temporary measurement coordinate system, using said mathematical tangents of the viewing angles of said first point in said first and second measurement coordinate systems and the relationships between said first and second camera viewing positions and said first and second camera spatial orientations determined in said external coordinate system, wherein said first temporary coordinate system has an origin and wherein said origin has a vector location in said external coordinate system;

(h) calculating a vector location of said first point in said external coordinate system by adjusting the vector location of said first point in said first temporary measurement coordinate system according to said first and second camera spatial orientations;

(i) acquiring a first image of a second point of said pair of points on the object with one of said one or more cameras located at a third viewing position, said camera having a third spatial orientation at said third viewing position, thereby defining a third measurement coordinate system which is coincident with the internal coordinate system of said camera at said third viewing position;

(j) acquiring a second image of said second point of said pair of points on the object with one of said one or more cameras located at a fourth viewing position, said camera having a fourth spatial orientation at said fourth viewing position, thereby defining a fourth measurement coordinate system which is coincident with the internal coordinate system of said camera at said fourth viewing position, and wherein at least one of said third and fourth viewing positions is different from either of said first and second viewing positions;

(k) measuring the coordinates of said first image of said second point in said third measurement coordinate system and measuring the coordinates of said second image of said second point in said fourth measurement coordinate system;

(l) correcting the measured coordinates of the first image of said second point to adjust for any distortion of the camera located at the third viewing position, and correcting the measured coordinates of the second image of said second point to adjust for any distortion of the camera located at the fourth viewing position, thereby producing first and second final second point image coordinates for said third and fourth viewing positions in said third and fourth measurement coordinate systems;

(m) multiplying the first final second point image coordinates by the mathematical inverse of the effective focal length of the camera located at the third viewing position and multiplying the second final second point image coordinates by the mathematical inverse of the effective focal length of the camera located at the fourth viewing position, to determine the mathematical tangents of the angles at which said second point is viewed in said third and fourth measurement coordinate systems;

(n) forming a least squares estimate of the three dimensional coordinates of said second point in a second temporary measurement coordinate system, thereby forming an estimate of the vector location of said second point in said second temporary measurement coordinate system, using said mathematical tangents of the viewing angles of said second point in said third and fourth measurement coordinate systems and the relationships between said third and fourth camera viewing positions and said third and fourth camera spatial orientations determined in said external coordinate system, wherein said second temporary coordinate system has an origin and wherein said origin has a vector location in said external coordinate system;

(o) calculating a vector location of said second point in said external coordinate system by adjusting the vector location of said second point in said second temporary measurement coordinate system according to said third and fourth camera spatial orientations;

(p) calculating the vector location of the origin of the first temporary coordinate system by forming the average of the camera location vectors for the first and second camera viewing positions;

(q) calculating the vector location of the origin of the second temporary coordinate system by forming the average of the camera location vectors for the third and fourth camera viewing positions;

(r) calculating a vector from the origin of the second temporary coordinate system to the origin of the first temporary coordinate system by subtracting the vector location of the origin of the second temporary coordinate system from the vector location of the origin of the first temporary coordinate system;

(s) calculating the vector from the second point of said pair of points to the first point of said pair of points with the equation

$$\mathbf{r} = \mathbf{d}_{AB} + \mathbf{r}_{AG} - \mathbf{r}_{BG}$$

wherein $\mathbf{d}_{AB}$ is the vector from the origin of the second temporary coordinate system to the origin of the first temporary coordinate system, $\mathbf{r}_{AG}$ is said vector location of said first point in said external coordinate system, and $\mathbf{r}_{BG}$ is said vector location of said second point in said external coordinate system; and

(t) calculating the distance between said pair of points by calculating the length of the vector $\mathbf{r}$.

10. An apparatus for measuring three - dimensional distances between selected points on an inaccessible object, wherein the apparatus includes a rigid borescope which is fastened to a linear motion means, said linear motion means having a range of travel and which also constrains the borescope to move along a substantially straight line, said apparatus further comprising a driving means which controls the position of the linear motion means within its range of travel and also a position measurement means for indicating the position of said linear motion means, characterized by the use of a linear motion means selected from the group consisting of crossed roller slides and ball slides and air bearing slides and dovetail slides, wherein the linear motion means is preferably a linear translation stage, the driving means is preferably an actuator, and the position measurement means is preferably a linear position transducer attached to said translation stage.

11. An apparatus for measuring three - dimensional distances between selected points on an inaccessible object, wherein the apparatus includes a rigid borescope which is fastened to a linear motion means, said linear motion means having a range of travel and which also constrains the borescope to move along a substantially straight line, said apparatus further comprising a driving means which controls the position of the linear motion means within its range of travel and also a position measurement means for indicating the position of said linear motion means, characterized by the use of a lead screw and nut as a driving means and, optionally, wherein both the driving means and the position measurement means are embodied in a micrometer.

12. An apparatus as claimed in either of claim 10 or claim 11 wherein said borescope has a field of view, and wherein said borescope includes a video imaging means, and wherein said video imaging means is comprised of a video sensor optically coupled to said borescope, and wherein said video sensor has different spatial resolutions along its two sensing axes, characterized in that said video sensor is rotationally oriented with respect to said borescope such that its higher spatial resolution axis is aligned substantially parallel to the projection of the linear motion of the borescope as observed in the field of view, thereby obtaining the highest precision in the distance measurement.

13. An electronic measurement borescope apparatus for measuring three - dimensional distances between selected points on an inaccessible object, characterized by:

(a) a video camera, including an imaging lens and a solid state imager, for producing video images of the object, and a video monitor, for displaying said video images;

(b) a linear translation means, for moving the video camera with a substantially constant orientation along a substantially straight line, said linear translation means and camera being disposed at the distal end of a rigid probe, and said linear motion means also having a range of travel;

(c) an actuating means, for moving the linear translation means to any position within its range of travel;

(d) a position measurement means, for determining the position of the linear translation means within said range of travel, whereby the position of the video camera is also determined, said position measurement means also producing position measurement data, said position measurement means also having a first data transfer means for supplying the camera position data to a computing means;

(e) a video cursor means, for displaying variable position cursors on said video image, said video cursor means having a second data transfer means for supplying the spatial positions of said variable position cursors to the computing means; and

(f) said computing means having a user interface, said user interface being in communication with said video cursor means and said second data transfer means such that a user can manipulate said video cursor means until said variable position cursors are aligned with the images of said selected points on said inaccessible object, and further such that said spatial positions of said variable position cursors are supplied to the computing means at user command, and further such that said computing means receives the camera position data through said first data transfer means, and further such that said computing means calculates and displays the three - dimensional distances between the selected points on said inaccessible object.

14. An apparatus as claimed in claim 13, characterized in that the actuating means is a motorized micrometer driving a positioning cable, said cable being looped around a pair of idler pulleys and being attached to the linear translation means or in that the actuating means is a motorized micrometer located at the distal end of said rigid probe, said motorized micrometer being attached to the linear translation means.

15. An electronic measurement endoscope apparatus for measuring three - dimensional distances between selected points on an inaccessible object, characterized by:

(a) a video camera, including an imaging lens and a solid state imager, for producing video images of the object, and a video monitor, for displaying said video images;

(b) a linear translation means, for moving the video camera with a substantially constant orientation along a substantially straight line, said linear translation means also having a range of travel, and said linear translation means and camera being disposed internally into a rigid housing, said rigid housing being disposed at the distal end of a flexible endoscope housing;

(c) an actuating means, for moving the linear translation means to any position within its range of travel;

(d) a position measurement means, for determining the position of the linear translation means within said range of travel, whereby the position of the video camera is also determined, said position measurement means also producing position measurement data, said position measurement means also having a first data transfer means for supplying the position measurement data to a computing means;

(e) a video cursor means, for displaying variable position cursors on said video image, said video cursor means having a second data transfer means for supplying the spatial positions of said variable position cursors to the computing means; and

(f) said computing means having a user interface, said user interface being in communication with said video cursor means and said second data transfer means such that a user can manipulate said video cursor means until said variable position cursors are aligned with the images of said selected points on said inaccessible object, and further such that said spatial positions of said variable position cursors are supplied to the computing means at user command, and further such that said computing means receives the camera position data through said first data transfer means, and further such that said computing means calculates and displays the three - dimensional distances between the selected points on said inaccessible object.

16. An apparatus as claimed in claim 15, characterized in that the actuating means is a positioning wire encased in a sheath, which is driven by a motorized micrometer, or in that the actuating means is a motorized micrometer located at the distal end of the apparatus, said motorized micrometer being attached to the linear translation means.

17. An apparatus as claimed in any one of claims 13 to 16, wherein said video camera has a field of view, and wherein an illumination means for illuminating said field of view is being carried by the linear translation means, characterized in that the illumination of said field of view remains substantially constant as said camera is moved.

18. An apparatus for making measurements of the three-dimensional distances between selected points on an object, said apparatus including a camera, and a support means, whereby said camera can be moved along a substantially straight translational axis from a first viewing position to a second viewing position as part of the measurement process, and whereby said camera can also be rotated about a rotational axis for alignment with objects of interest prior to a measurement, said rotational axis being at an arbitrary alignment with said translational axis, characterized by:

(a) a means for measurement of an angle of rotation of said camera about said rotational axis; and

(b) a means for incorporating said measurement of said angle of rotation into said measurements of three-dimensional distances.

19. An apparatus as claimed in claim 18 characterized in that said means for measurement of an angle of rotation has a first portion which rotates with said camera and also has a second portion which is fixed to said support means, wherein said camera is preferably a substantially side-looking rigid borescope, said borescope having a lens tube envelope and said lens tube envelope having an outer surface, and wherein said support means preferably comprises a borescope positioning assembly and wherein said rotational axis is preferably defined by the engagement of a first reference surface attached to said borescope with a second reference surface attached to said borescope positioning assembly, whereby said first reference surface is preferably a cylinder and said second reference surface is preferably a V groove, and said cylindrical first reference surface is said outer surface of said lens tube envelope or is a calibration sleeve attached to said borescope.

20. An apparatus for making measurements of the three-dimensional distances between selected points on an object, said apparatus including a substantially side-looking rigid borescope which can be moved along a substantially straight translational axis from a first viewing position to a second viewing position as part of the measurement process, wherein said borescope can also be rotated about a rotational axis for alignment with objects of interest prior to a measurement, characterized by the arrangement of said rotational axis to be accurately aligned with said translational axis.

21. An apparatus as claimed in claim 20 wherein said borescope has a lens tube envelope and said lens tube envelope has an outer surface, characterized in that said borescope is preferably moved along said translational axis by a borescope positioning assembly and said rotational axis is preferably defined by the engagement of a first reference surface attached to said borescope with a second reference surface attached to said borescope positioning assembly, whereby said first reference surface is preferably a cylinder and said second reference surface is preferably a V groove, and said cylindrical first reference surface is said outer surface of said lens tube envelope or is a calibration sleeve attached to said borescope.

22. An apparatus for measuring three - dimensional distances between individual user selected points on an inaccessible object, wherein the apparatus includes a rigid borescope which is fastened to a linear motion means, said borescope forming an image of said points on said object and said linear motion means having a range of travel and which also constrains the borescope to move along a substantially straight line, said apparatus further comprising a position measurement means for indicating the position of said linear motion means within its range of travel, and also an image measurement means for determining the positions of said selected points in said image, said apparatus further comprising a computation means for incorporating said positions of said selected points in said image and said position of said linear motion means into a calculation of said three dimensional distances, characterized by a computation means that is programmed to perform a fully three - dimensional least squares estimation procedure to determine the measurement result.